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USAF TECHNICAL REPORT NO. 5829

# PSYCHOLOGICAL ASPECTS OF EQUIPMENT DESIGN

Paul M. Fitts

August 1949



Published by
UNITED STATES AIR FORCE
AIR MATERIEL COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, DAYTON, OHIO

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# PSYCHOLOGICAL ASPECTS OF EQUIPMENT DESIGN

Paul M. Fitts
Chief, Psychology Branch
Aero Medical Laboratory

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# ABSTRACT

Human Engineering concerns the design of equipment and man-machine systems in relation to the abilities of human operators. It is a new field of applied science. Its data are drawn from psychology, anthropology, biophysics, engineering, and many other sources. The present report is a systematic review of psychological facts and experimental results of significance for human engineering.

Systems research is considered first. It contributes to the discovery of critical human "links" and sources of human error in man-machine systems. The design of visual, auditory, and tactual displays are considered next. Here many problems of transmitting and presenting information are considered. The design of controls is treated next. This last section is organized around the concept of man as a link in a control system. Dynamic aspects of human controller processes are considered in relation to servo engineering. Optimum location and mode of actuation of controls are among the problems treated.

PUBLICATION APPROVAL

For the Commanding General:

A. P. Gagge

A. P. GAGGE
Lt. Colonel, MSC (USAF)
Acting Chief, Aero Medical Laboratory
Engineering Division

FOREWORD

This report is based on a chapter written by Dr. Paul M. Fitts, Chief of the Psychology Branch, Aero Medical Laboratory for inclusion in a Handbook of Experimental Psychology. The kindness of the publishers, John Wiley and Sons, Inc., and of the Editor, Dr. S. S. Stevens of Harvard University in permitting the writer to reproduce the material in this chapter and to distribute it to a limited number of engineers and government contractors is gratefully acknowledged. Adaptation of the manuscript for publication as a USAF Technical Report has been accomplished under Expenditure Order No. 694-36.

The report is written primarily for research workers and for graduate students who are majoring in general and applied experimental psychology. However, it should be of equal interest to design engineers.

The facts reviewed in the report have been drawn from many publications, some more than half a century old. However, recent research studies originating in the psychology laboratories of universities working on Government contracts and in the Psychology Branch, Aero Medical Laboratory, have been drawn on heavily. The author wishes to express his indebtedness to the staff of the Psychology Branch, and in particular to Dr. W. F. Grether, Dr. W. C. Biel, Mr. J. M. Christensen and Mr. M. J. Warrick for many of the ideas incorporated in the report. The assistance of Major R. C. Gibson, Department of Electrical Engineering, USAF Institute of Technology, in formulating the sections on dynamic aspects of controller processes is also acknowledged.

The information covered in the report is drawn entirely from unclassified publications.

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# PSYCHOLOGICAL ASPECTS OF EQUIPMENT DESIGN

Traditionally the design of machines has been a responsibility of engineers and the discovery of the most effective procedures for selecting and training men to use them has been a task for psychologists. Before machines are ever built, however, it is sensible to consider how well human beings will be able to use them, and to select machine designs that will insure that the final product is adapted for rapid learning and efficient human use.

From this point of view psychology and engineering have the common problem of designing equipment to meet human requirements. Until recently, the psychological aspects of machine design have been conspicuously neglected. Psychologists have usually accepted the engineer's handiwork as a *fait accompli* and have limited their efforts to the study of means for assisting men to adapt to existing machines.

The demands of World War II finally brought the many problems of equipment design forcefully to the attention of experimental psychologists. Early in the war several laboratories undertook extensive programs of research in this field. In particular, the Applied Psychology Unit at Cambridge University, England, began investigations of sensory and motor problems in equipment design, and the Psycho-Acoustic Laboratory at Harvard University turned its efforts to the study of psychological problems in the design of communication equipment. By the end of the war psychologists were conducting investigations relating to the design of such varied equipments as radar consoles and scope faces, instrument dials, binoculars, stereoscopic height-finders, gunsight reticles, underwater sound-detection devices, voice communication systems, signal systems, gunsight controls, aircraft cockpits, combat information centers, and synthetic training devices. Since the war, research of this nature has continued on a relatively large scale. Much of the material in the present chapter is taken from this recent work.

Psychological research on equipment-design problems has been identified by various names. Among these are applied experimental psychology, applied psychophysiology, man-machine systems research, biotechnology, psychotechnology, human engineering, and engineering psychology. Convention favors the name *engineering psychology*, since it conforms to the practice followed in naming other specialized areas such as educational, clinical, personnel, and industrial psychology. Hereafter, engineering psychology and equipment-design research will be used synonymously.

It is the purpose of the present chapter to summarize psychological facts and principles of particular significance for equipment design, to point out gaps in our basic information, and to indicate theoretical questions raised by the study of man's behavior in using the mechanical devices of our technological society.

## PROBLEMS AND METHODS IN ENGINEERING PSYCHOLOGY

An applied science must define its problems and then foster research programs directed at systematic investigation of the ones that appear most important. Once problems are defined and techniques of investigation perfected, research in areas of practical or social significance can proceed in the same manner as in any well-established discipline.

Research Techniques. The methods employed in research on equipment problems are primarily those of experimental psychology. However, techniques from various applied fields are sometimes used, such as those of paper-and-pencil testing, non-structured interviewing, and motion-and-time study. Experimental designs that permit the simultaneous study of a number of variables, and of their interaction effects, have been found to be especially productive.

Methodological problems peculiar to this new research field are far too numerous to permit even a listing in the present chapter. They range from criterion problems to problems of electronic circuitry, from questions of how to handle skewed distributions of error frequencies in dial-reading studies to questions of how to measure stimulus-response relationships in continuous tasks.

Many areas of equipment-design research call for systematic, large-scale programs of investigation. These programs should be planned on the basis of empirical findings as to the most important problems within the particular area or man-machine system concerned. Several effective survey techniques are now available for securing such empirical data. These survey techniques deserve brief consideration here. They are not procedures that one would use in carefully controlled experiments so much as techniques for identifying, analyzing, and defining problems within the field of engineering psychology.

The Discovery and Definition of Critical Problems in Designing Man-Machine Systems. Different elements in a complex man-machine system contribute to the overall error variance of the system in accordance with a well-known statistical relationship (Chapanis, 1949). If the total variable error in a system is represented by $\sigma_T$, then additive

components a, b, c, ... of the system contribute to this total in accordance with the relation

$$\sigma_T^2 = \sigma_a^2 + \sigma_b^2 + \sigma_c^2 + \cdots \tag{1}$$

provided the errors contributed by each of the components are uncorrelated. Otherwise the relationship is

$$\sigma_T^2 = \sigma_a^2 + \sigma_b^2 + \sigma_c^2 + \ldots \pm 2r_{ab}\sigma_a\sigma_b \pm 2r_{ac}\sigma_a\sigma_c \pm 2r_{bc}\sigma_b\sigma_c \pm \cdots \tag{2}$$

It is apparent that the relative importance of the root-mean-square error contributed by any component increases quadratically with its relative size. It follows that improvement in the more accurate elements of a system will produce only a negligible reduction in the total variable error of the system. For example, if the machine components of a particular man-machine system contribute a root-mean-square error of 10 and the human components contribute an error of 50, and the two are unrelated, the variable error of the total system is only 51. In this case only a 2 per cent improvement in the system would be gained by eliminating all the variable errors of the machine components. Chapanis and his associates (1949), developing this line of statistical inference, have shown that it is possible to analyze the errors in complex machine operations and industrial processes, and to determine the relative size of the error variance contributed by men, by machines, and by interaction effects.

Correlation techniques can be used in studying sources of difficulty in technical tasks. Carter and Dudek (1947), for example, secured records from standardized navigation flights. Applying factor-analysis and multiple-correlation techniques, they found that three principal factors -- heading, speed, and wind effect -- determined the accuracy of navigators' position reports. The most important single source of error was concluded to lie in the determination of compass deviation, i.e. in the measurement of the discrepancy between compass heading and magnetic heading. This error was then traced to a particular instrument, the astro-compass.

Christensen (1949) used an activity-sampling technique to advantage in analyzing and quantifying the activities of men engaged in complex tasks. In one instance he recorded at 5-second intervals the operations performed by aerial navigators and radar operators during 15-hour flights. An analysis of the resulting data enabled him to make precise estimates of the amount of time devoted to each of a large number of activities, to determine the sequences in which activities were performed, and to infer from these data where the greatest amount of time could be saved by new equipment and by revised operating procedures.

A further survey technique that is useful when one is exploring a new area of engineering psychology is the critical-incident technique. Fitts and Jones (1947, 1947a), for example, asked pilots for detailed descriptions of specific errors or difficulties experienced in operating controls and in responding to instruments. These descriptions of critical experiences were classified and enumerated. The results for instrument-reading errors are given in Table I. Findings from several experimental studies of problems revealed by this survey will be discussed later. Similar to the critical-incident technique is the procedure of analyzing and classifying recorded or observed errors in equipment use. Reports by Ford (1949) and Grether (1949) illustrate this approach.

It is desirable at times, as a further step in defining problems, to ask experienced persons to rate the frequency of use, and the importance, of different components, processes, or "links" in a system.

A good deal of emphasis has been given in recent years to systems research. Systems studies have often been concerned with such practical problems as the optimum number of human operators that should be assigned to work in a particular system, the optimum number and kind of equipment components that should be used in the system, and the optimum arrangement of men and machines. Motion and time engineers, attempting to discover the most efficient methods of work, have collected similar data and reported "link values", "therblig values", processes charts, and time charts for many industrial tasks. For the most part, systems studies such as these are relevant to experimental psychology only insofar as they indicate problems for experimental study. In this respect, however, they have made an important contribution to research on equipment design.

Numerous authors have attempted to classify and assign importance to problems within the field of engineering psychology. Representative discussions are found in publications by Bartlett (1947), Bray (1948), Brown and Jenkins (1947), Chapanis, Garner and Morgan (1949), Fitts (1947), Grether (1947), Kappauf (1949), McFarland (1946), Mead (1948), and Morgan (1947). However, the time does not yet appear appropriate for proposing a final classification scheme for the problems within engineering psychology. The major distinction made by the present writer is between display problems, i.e. questions of how best to present information to the senses, and problems of the design of control systems, i.e. questions of how best to utilize human motor output and how to secure good dynamic characteristics in complete controller systems.

The objectives that have been set for most of the research programs in engineering psychology have been economy in training and improvement in final efficiency. Other considerations are the increase of safety, the protection of workers from unusual stresses, the increase of personal satisfactions derived from operating a machine, and the opening of new tasks to less intelligent or less skillful individuals. These additional objectives deserve serious attention.

TABLE I

CLASSIFICATION OF 270 ERRORS MADE BY AIRCRAFT PILOTS IN RESPONDING TO INSTRUMENTS AND SIGNALS*

| | Relative Frequency |
|---|---|
| 1. Misinterpreting Multi-Revolution Instruments. Mistakes in comprehending information presented by two or more pointers or by a pointer plus a rotating dial viewed through a "window" | 18 |
| 2. Misinterpreting Direction of Indicator Movement (Reversal Errors). Improper interpretation of an instrument indication with the result that subsequent actions increase rather than reduce an undesirable condition. | 17 |
| 3. Misinterpreting Visual and Auditory Signals. Failing to respond appropriately to hand signals, warning lights or sounds, or radio range signals. | 14 |
| 4. Errors Involving Poor Legibility. Difficulty in seeing numerals, scale markings, or pointers clearly enough to permit quick and accurate reading. | 14 |
| 5. Failing to Identify a Display. Mistaking one instrument for another or confusing pointers on a multiple-pointer display. | 13 |
| 6. Using an Inoperative Instrument. Accepting as valid the indication of an instrument that is inoperative or operating improperly. | 9 |
| 7. Misinterpreting Scale Values. Difficulty in interpolating between numbered scale graduations or failure to assign the correct value to a numbered graduation. | 6 |
| 8. Errors Associated with Illusions. Difficulties arising out of a conflict between body sensations and information given by visual displays. | 5 |
| 9. Omitting the Reading of an Instrument. Failing to refer to an instrument at the proper time. | 4 |
| Total | 100 |

*Modified slightly from Fitts and Jones, 1947a

One further point should be emphasized. Research in engineering psychology must concern itself with the behavior of individuals in complex and continuous tasks, particularly tasks in which skill is exercised, not in the use of manual tools, but in the rapid interpretation of instruments or signals and in the accurate control over sources of external power. Furthermore, machines usually must be designed, not with reference to any one factor, but with reference to many complex and sometimes conflicting considerations. In the present chapter, therefore, emphasis is given to experimental data relating to complex skills, to interaction effects, and to human performance in a variety of different tasks.

## DESIGN OF VISUAL DISPLAYS

A display is any device that can be used for presenting information to individuals by visual, auditory, tactual, or other exteroceptive channels.

The general requirements of good visual displays are perhaps obvious. However, they warrant a brief listing. Visual displays should be sufficiently above threshold to permit quick and accurate discrimination, and they should vary over a sufficient number of discriminable steps to permit adequate gradation of motor responses. Displays should present information in such a manner that it can be interpreted easily, and utilized either at a conceptual level in making judgments and decisions, or at a perceptual-motor level in carrying out complex control tasks. Furthermore, most displays should be designed so that they can be employed for a variety of different purposes and used under a wide range of conditions. It is a simple matter to state such general requirements. It is not so easy to specify how these requirements can be met. However, this is the problem with which we are concerned.

Significance of Different Visual Discrimination Processes. The literature on visual discrimination includes reports of performance in many different tasks, varying from detection of the presence of light energy to recognition of complex patterns. These different visual tasks often are relatively unrelated. This is illustrated by one of Forbes and Holmes' (1939) studies of highway signs. After determining the maximum distance at which 24-inch roadside warning symbols could be recognized with unlimited time, they had subjects drive along an unfamiliar road and call out all signs as soon as they were observed. Calls occurred at distances of 200 to 400 feet in contrast with the 800 or more feet at which similar symbols were recognized on the previous tests. In applying the results of studies of different discrimination processes to equipment-design problems, caution must be exercised in generalizing beyond the specific task performed by the subject.

Two distinctions regarding visual discrimination tasks are especially important. One is the distinction between the detection of the mere presence of a visual stimulus, and the discrimination of form or pattern. The other is the distinction between tasks in which little interest is attached to the time required for the completion of a response to a visual stimulus, and tasks in which the time interval between the exposure of a stimulus and the completion of a verbal or motor reaction is of primary interest. Investigations that place no emphasis on response time, regardless of whether the stimulus is presented for only a fraction of a second or for an unlimited time, will be called visibility studies. Most investigations of minimum visible acuity and minimum separable acuity are examples of visibility studies. Investigations emphasizing the overall time required for discrimination and response will be called legibility studies. For the most part visibility studies have been concerned with the discrimination of very simple forms, and legibility studies with the discrimination of complex patterns such as those on the printed page. Studies emphasizing pattern discrimination are often said to provide "identifiability" thresholds. The contributions of visibility studies of equipment-design will be considered first.

## Design Problems Involving Visibility and the Discrimination of Small Differences

Since adequate visibility is a prerequisite for all visual displays, a few illustrations will be given to show the application of basic data on visibility to equipment-design problems.

Size, Brightness, and Contrast. The design of radar (radio detection and ranging) equipment raises many problems of visual discrimination. Radar operators frequently are forced to search for weak signals that are at near-threshold levels. The effectivenss of radar displays, therefore, is critically determined by such factors as the size, brightness, and contrast of visual stimulus objects. The importance of these psychological factors in the operational use of radar has been emphasized by Stevens (1946).

Radar information is usually displayed on the face of a cathode ray tube (CRT). Pulses of electrical energy are sent out by the radar and reflected back by the target, whereupon they are amplified and usually made to modulate the intensity of a beam of electrons in the CRT in such a way that corresponding to each target there appears a bright spot or a "pip"on the face of the tube. In practice, radar returns are almost always accompanied by "noise", so that the real targets are partially or completely obscured by a background of random brightness variations on the face of the CRT.

The visibility of radar signals, either with or without a noise background, was shown (Williams et al., 1948) to vary with CRT brightness in about the same manner as does the visibility of laboratory test objects. A slight loss in visibility was found for small values of CRT bias (bright traces), but it was discovered that this was due to loss of sensitivity of the phosphor screen with resulting loss of contrast at higher beam intensities.

The brightness adaptation of the eye and the level of brightness of the area surrounding the target are factors that influence the visibility of displays such as those on a radar scope. Hanes and Williams (1948) found that for weak radar signals the lowest contrast thresholds and the shortest detection times occurred when the test and adapting illuminations were approximately equal in brightness. These results were obtained for adapting brightness levels ranging from 0 to 1858 foot lamberts and for screen intensities ranging from 0.00009 to 0.204 foot lamberts. Similar results have been reported from several related studies. For optimum detection of low-contrast "pips" the CRT should be adjusted until the background brightness of the tube is in the neighborhood of 0.1 foot lambert. It has also been found that ambient illumination as bright as the screen background has no detrimental effect on CRT target visibility and may actually improve it, by permitting the maintenance of relatively uniform retinal adaptation at a level near the optimum.

A preliminary investigation of visibility of CRT signals as a function of their size has been reported by Bartlett and Williams (1947). The smallest image size employed subtended 1 minute by 12 degrees of visual angle at a viewing distance of 12 inches. It was found that very dim targets could be discriminated more readily if the eyes were near the scope face (as close as 6 inches) than if they were farther away (24 inches). This finding was true for dark or moderately bright CRT backgrounds but did not hold when noise was present. In an unpublished study from the Applied Psychology Unit of Cambridge University, it was also found that varying the viewing distance from 10 to 18 inches had no effect on the visibility of a small target when noise was present. Detection of targets viewed against a noise background involves pattern perception, of course, rather than simple brightness discrimination. The role of stimulus size apparently varies, therefore, depending on whether the task involves the visibility or identifiability of a target.

The detection of a low-intensity image that is viewed among a cluster of relatively bright noise pips is much more difficult than the identification of the same image when it is seen against a uniform background. Payne-Scott (1948) has discussed the importance of this point and suggested procedures for simplifying the radar operator's task. One of her suggestions, stated briefly, is to increase the number (N) of samples of noise per unit of time, thus obtaining a more even distribution of noise over the surface of the tube face. This suggestion is based on the fact that both the human eye and the phosphor of the tube

have relatively long response times, and hence act in combination to integrate or smooth out in time the individual noise returns at any particular point on the tube face, provided the separate noise returns do not occur too far apart in time. Engineers can vary approximately 15 design characteristics that have an effect on the equivalent N of a radar set or on the size, brightness, or contrast of the target.

It appears that the ability of an operator to detect radar images can be predicted from existing visibility data. However, it is often desirable to repeat classical visibility determinations under conditions that permit the study of special interaction effects and limiting conditions peculiar to radar displays.

Color. The wave length of the light reflected by a display is sometimes an important design factor. Monochromatic red light is especially advantageous when it is necessary to read instruments and to preserve dark adaptation at the same time. This is true because the visual receptor elements that mediate night vision are relatively insensitive to red light. It was not until late in World War II, however, that red light came into general use for the illumination of instrument panels.

Since the eye is not color corrected it cannot bring all wave lengths of light into simultaneous focus on the retina. This suggests that monochromatic light may give better visibility than light of mixed wave-length. Kappauf (1949), in a review of data bearing on this point, concluded that the evidence is contradictory. Among monochromatic lights, yellow provides the best acuity.

Visibility of numerals and letters printed in various color combinations has been found (Preston *et al.*, 1932; Sumner, 1932) to depend primarily on brightness and contrast, rather than on color. Data collected by Eastman Kodak Company (1944) now make it possible to compute the equivalent brightness contrast of two monochromatic fields that are of the same apparent brightness. Thus color differences can be expressed as equivalent brightness differences.

Pattern discrimination theoretically is a function of the ability to detect gradients of brightness, color, and saturation. Few displays except those employed in color motion pictures and color television, however, employ all three factors. The science of camouflage, of course, makes extensive use of all three factors in attempting to destroy pattern vision for objects by making them blend in with their background or assume deceptive configurations.

Vernier Acuity. Vernier acuity, measured in terms of the minimum displacement necessary for two portions of a line to be perceived as discontinuous, is much more precise than minimum separable acuity.

It is a form of discrimination that in many instances determines how accurately an instrument can be read. However, in spite of the fact that the reading of a great many measuring instruments depends upon the principle of vernier acuity, very few studies have been made of the stimulus variables that influence this aspect of scale-reading tasks.

<u>Discrimination of Velocity and Changes in Velocity</u>. If an individual can respond to the velocity and acceleration of a moving object, i.e. respond in anticipation of its future course, he can perform many perceptual-motor tasks much more effectively than if he responds only to the object's position from moment to moment. Hick (1948) found that the ability to detect a sudden change in the velocity of a moving spot on a CRT obeys Weber's law approximately; the mean threshold (50 percent probability of detection) averaged about 12 percent of the initial velocity under favorable conditions. No data are available on the ability to detect changes in acceleration. It seems likely, however, that it would be very difficult to make such judgments.

<u>Discrimination of Three Coordinates from Cues Provided by a Single Image on a Cathode-Ray Tube</u>. Numerous efforts have been made to provide more than two parameters of information from a single image on a CRT. These efforts have been concerned primarily with the representation of the location of objects in three-dimensional space.

Any two of the three coordinates necessary to locate an object in space can be represented by the position of the CRT image with reference to a polar or rectangular grid system superimposed on the tube face. Difficulties arise when we try to add the third dimension. The use of stereoscopic devices has been considered as a means of adding apparent depth to displays. Most efforts to solve this problem, however, have made use of changes imposed on the image itself, such as changes in its size, brightness, color, or pattern, or of changes in its temporal characteristics, such as flicker rate. Several of the many possibilities are illustrated in Fig. 1. Thus we see that man's ability to make relative or absolute discriminations of stimulus values is an important consideration in designing "three-dimensional" displays.

<u>Discrimination of Angular Position</u>. On many circular instruments, values are indicated by the angular position of a hand or cursor. Sometimes it is necessary for individuals to judge directly the angle formed by two such objects or lines, or by one object with respect to the vertical and horizontal. This ability has been studied by the staff of the Psychological Research Unit at Mount Holyoke College, using lines projected on a large unstructured circular screen (Kaufman <u>et al</u>., 1947; Reese <u>et al</u>., 1948; Rogers <u>et al</u>., 1947).

The average error of 33 subjects in judging the bearing of a line of light was 2.8 degrees. Subjects adjusted a marker to a designated bearing more accurately than they estimated the bearing of a marker

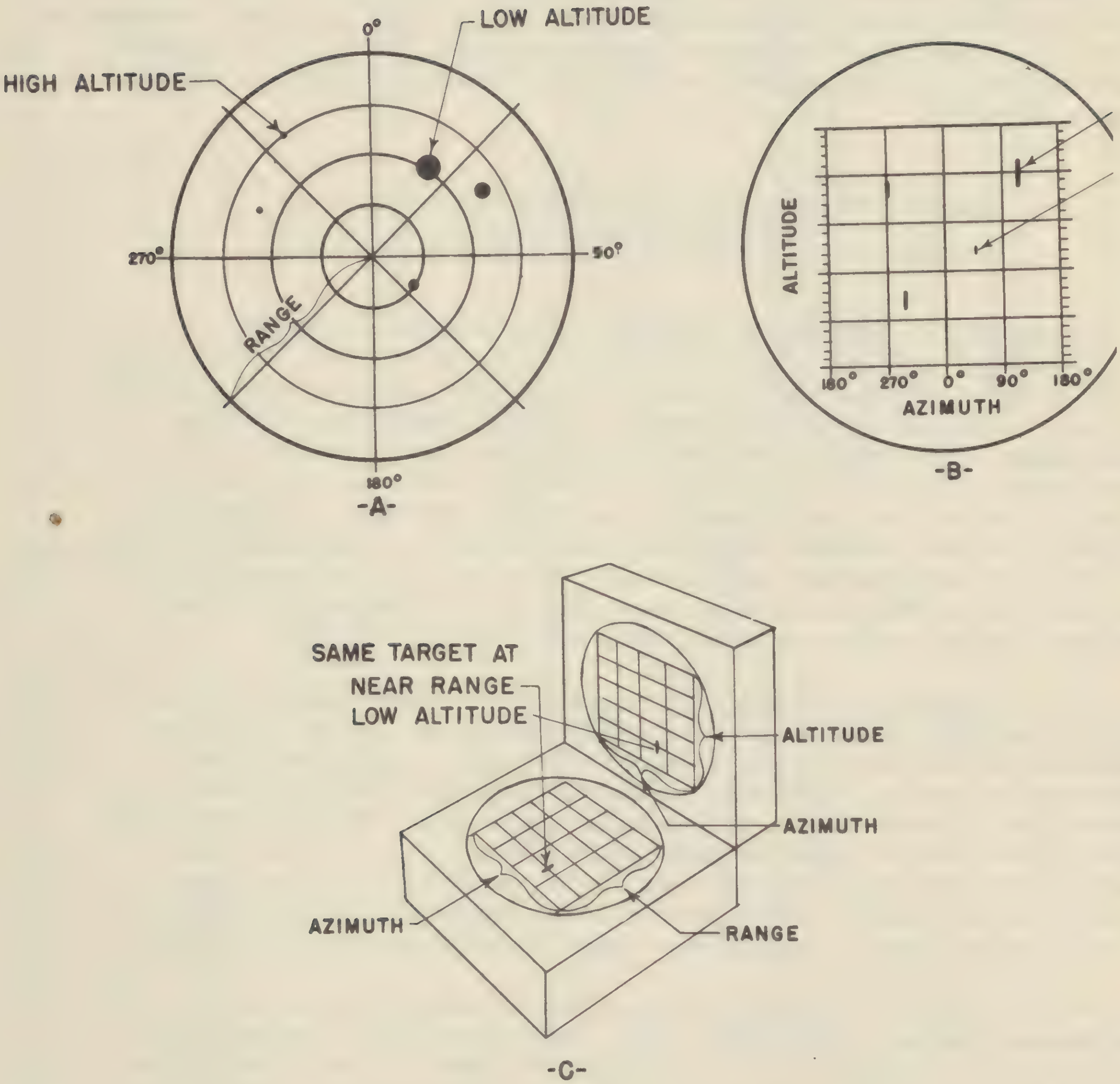



Fig. 1. Three of the many possible ways of displaying three dimensions of information on two-dimensional CRT surfaces. In A and B the size and length respectively of the "blip" are utilized to indicate the relative magnitude of the third dimension; in C two separate "blips" are employed to represent the position of a single object.

that had already been adjusted, but adjustment required more time than estimation. The introduction of a known reference line enabled observers to reduce their errors in estimating bearings that were as far as 20 to 30 degrees from the reference. When no visual reference was provided, reliance was placed on subjective estimates of the vertical and horizontal. Estimates were most accurate at the 0- and 90-degree points, and somewhat better at 45 degrees than at other bearings in the 0- to 90-degree sector. On the basis of these and related investigations, a grid system of 24 bearing markers spaced 15 degrees apart was recommended for use on large display screens (Kaufman et al., 1947). Such a grid system includes all the salient or "natural" anchor points (0, 30, 45, 60, 90, etc. degrees).

## Design Problems Involving Speed and Accuracy of Pattern Discrimination

Standards for Legibility Studies. In studying legibility or identifiability problems some investigators have recorded both time and errors, others only one or the other. Some have employed modifications of visual acuity measurements, such as maximum distance for quick recognition. One worker combined time, errors, and variability into a single index. The lack of standard procedures and standard units has seriously limited the usefulness of legibility studies. Fortunately, agreement has been reached regarding certain units of measurement and conditions of experimentation, through the work of a sub-committee of the Armed Forces-NRC Vision Committee (1947). The recommendations formulated by this sub-committee are summarized in Table II.

Size of Numerals and Letters. Burnham, in 1892, concluded that printed characters should have a minimum height of 1.5 mm. This is equivalent to the size of small letters printed in 10-point type. Interestingly enough, subsequent work supports this early observation. Paterson and Tinker (1940), for example, found that the use of 6- and 8-point type retards speed of reading, but that 9-, 10-, 11-, and 12-point type are about equally legible when each is used with an appropriate line width. Most journals and textbooks are printed in 10- or 11-point type. Readers have been found to prefer this size.

Reading speed is retarded if type is too large (Buckingham, 1931). Paterson and Tinker (1942, 1943, 1944) have shown that the average number of words covered per eye fixation is less for very large type than for type of an optimum size. Although fixations are somewhat shorter for large type than for small, the net result in one study comparing 10-point and 14-point type was found to be a 14-percent increase in perception time for the larger type. This is not strange when it is considered that 14-point type occupies 87 percent more printing space than 10-point type.

TABLE II

STANDARDS RECOMMENDED BY THE ARMED FORCES-NRC VISION COMMITTEE FOR USE IN RESEARCH ON VISUAL DISPLAYS

| Variable | Unit of Measurement | Standard | Remarks |
|---|---|---|---|
| **A. Subject Variables** | | | |
| 1. Visual Acuity | --- | 20/20 or better | Should be applied to each eye and to both near and far vision. Use of glasses is permitted. |
| 2. Color Vision | --- | "Normal" | Use any standard pseudo-isochromatic chart. |
| 3. Mental Ability | --- | None specified | Define population used with respect to sex, age, education, work experience, intelligence scores, and measures of perceptual, verbal, numerical, and motor abilities. |
| **B. Stimulus ("Controlled") Variables** | | | |
| 4. Distance | Feet and inches | 14 inches<br>28 inches<br>20 feet | Representative of normal reading distance.<br>Representative of instrument-reading distance.<br>Standard distance for visual acuity measurements. |
| 5. Size | Visual angle | --- | Express in degrees, minutes, and seconds. |
| 6. Height of Numerals | Inches | 3/32,1/8,3/16 | For minor, intermediate, and major numerals and letters on instruments to be viewed at 28 inches. |
| 7. Stroke Width of Numerals | Inches | 0.015, 0.020, 0.025 | For minor, intermediate, and major numerals, and letters on instruments to be viewed at 28 Inches. |

(continued)

TABLE II (continued)

STANDARDS RECOMMENDED BY THE ARMED FORCES-NRC VISION COMMITTEE FOR USE IN RESEARCH ON VISUAL DISPLAYS

| | Variable | Unit of Measurement | Standard | Remarks |
|---|---|---|---|---|
| 8. | Length of Scale Graduations | Inches | 3/32, 5/32, 7/32 | For minor, intermediate, and major graduations on instruments to be viewed at 28 inches. |
| 9. | Width of Scale Graduations | Inches | 0.015, 0.020, 0.025 | For minor, intermediate, and major graduations on instruments to be viewed at 28 inches. |
| 10. | Pointer Length | Inches | --- | Tip should reach the inner end of minor scale graduations. |
| 11. | Pointer Width | Inches | 3/32 | --- |
| 12. | Style of Numerals and Letters | --- | Aeronautical Design Standard No. AND 10400 | Wrico or LeRoy lettering guides are acceptable substitutes. |
| 13. | Color or Hue | Millimicrons | --- | Specify dominant wave length if possible, otherwise match with Munsell scale. |
| 14. | Saturation | Millimicrons | --- | Specify wave length distribution if possible, otherwise match with Munsell scale. |
| 15. | Brightness | Footlambert | 30 ft.L. for day simulation; 0.1 ft.L. for night simulation. | Use MacBeth Illuminometer or comparable photometric instrument. Brightness should be specified for the white area, whether figure or ground. |
| 16. | Illumination | Footcandles | --- | --- |

(continued)

TABLE II (continued)

STANDARDS RECOMMENDED BY THE ARMED FORCES-NRC VISION COMMITTEE FOR USE IN RESEARCH ON VISUAL DISPLAYS

| | Variable | Unit of Measurement | Standard | Remarks |
|---|---|---|---|---|
| 17. | Color of Figure and Ground | --- | Black on White<br>White on Black | For general use.<br>For instruments designed for night lighting. |
| 18. | Contrast | $\frac{DI}{I + DI}$ | --- | Maximum possible contrast is recommended. I in this case is the lesser of the two brightnesses. |
| 19. | Adaptation Level | --- | Allow sufficient time for eyes to adapt to test level | See S. Hecht, C. Haig, and A. M. Chase, The Influence of Light Adaptation on Subsequent Dark Adaptation of the Eye, J. Gen. Physiol., 1937, 20, 831-850. |
| 20. | Exposure Time | Seconds | 0.1 second | When a single eye-fixation is desired. |
| 21. | Style of Type | --- | --- | Follow recommendations in Paterson, D. B. and Tinker, M. A., How to Make Type Readable, pages 156-157. |

Paterson and Tinker, who have systematically investigated such typographic variables as size, style of type, width of line, space between lines, margins, columnar arrangement, space between columns, color of print and paper, and paper surface, stress the importance of interactions between these variables. They emphasize that interaction is the rule rather than the exception and they caution against drawing conclusions about optimum values for any variable that has been studied in isolation.

Size of Instrument Dials and Cathode Ray Tubes. The question of optimum size also arises in the design of scale markings, numerals, pointers, overlays, radar scopes, and many other items. Here an important consideration is whether the operator has plenty of time for reading, or whether he must check a display very quickly.

Check-reading requires rapid inspection in order to detect deviations outside the normal range. Under conditions that permitted subjects to respond to the patterns formed by a group of instruments, White (1949), found that a panel containing 16 instruments of 1 3/4-inch diameter was check-read somewhat more rapidly than panels of either larger or smaller instruments. Results were as follows for 24 subjects:

| Size of Individual Dials | Average Check-Reading Time | Frequency of Errors |
|---|---|---|
| 1 inch | 0.67 second | 5 percent |
| 1 3/4 inches | 0.65 second | 3 percent |
| 2 3/4 inches | 0.69 second | 6 percent |

The differences in both speed and error scores favored the intermediate over the large-size dials and were significant at better than the 5-percent level. Eye movement records also indicated that there were fewer fixations on the intermediate-size dials.

Studies of the size of radar scopes in relation to speed of target detection have also indicated an optimum size range. The optimum size is considerably less than that employed on some present-day cathode ray tubes. Where the use of a larger scope results only in distributing the existing signal over a larger surface, little gain in legibility is to be expected with scopes larger than about six inches in diameter (Horton, 1949). However, if CRT displays are designed to be viewed from a distance, or by several observers at once, as in the case of home television, larger sizes are often desirable.

Sleight (1948), using a 0.12-second exposure time, determined errors in reading linear, circular, and other types of scales to the nearest graduation mark. All scales covered a range from 0 to 10, and the distance between adjacent scale division marks was constant. The average errors made by 60 subjects and the maximum visible dimension of

each scale were as follows:

| Type of Scale | Maximum Dimension | Frequency of Errors |
|---|---|---|
| Open-window | 1 2/3 inches | 0.5 percent |
| Round dial | 2 1/6 inches | 10.9 percent |
| Semi-circular | 4 1/3 inches | 16.6 percent |
| Linear-horizontal | 7 inches | 27.5 percent |
| Linear-vertical | 7 inches | 35.5 percent |

All differences in error frequency were significant at the 1-percent level. It can be seen that there was a close relation between the maximum visible dimension of a scale and the observer's ability to read it during an exposure shorter than the time required for an average eye fixation. For such short exposures it appears that the best scale is the one that enables the reader to anticipate most precisely where to find the pointer.

Grether and Williams (1947) reported that there was no systematic relation between speed of reading and dial size for dials ranging in diameter from 1 to 4 inches when subjects had to call out numerical values. Kappauf and associates (1947, 1948) found no significant differences in quantitative-reading speed between 1.4- and 2.8-inch dials, but they reported a marked loss of speed for a 0.7-inch size. They also found that a general slowing of response accompanied any increase in the overall range of values depicted on a scale. For rapid detection of pattern changes or rapid reading of scales, it can be concluded that there is generally an optimum size of display.

A different principle holds when reading speed is not important. If similar information is presented on a large and on a small dial, then more accurate readings can usually be made from the larger dial, provided, of course, that the time permitted is adequate for quantitative reading and that an appropriate dial scale is used. Under non-speeded conditions the precision of reading has been found to be primarily a function of the arc-distance separating each unit of the scale. According to this principle the precision with which a circular instrument can be read is, within limits not yet determined, proportional to the circumference of the dial, in the same respect that precision, in the case of a linear instrument, is proportional to its length.

Spacing of Scale Marks. It is possible to vary the distance between scale marks as well as the overall size of a display. Three sets of studies are pertinent here. In all of these studies data were obtained for circular dials of approximately aircraft-instrument size (2 3/4-inch effective diameter). Loucks (1944) exposed four different types of dials for either 0.75 or 1.50 seconds in randomized sequence. An error was recorded whenever the reading differed from

the true setting by more than an arbitrary amount. Grether and Williams exposed single dials in a randomized sequence with instructions to work for speed, but permitted subjects to take as much time as necessary to read them and recorded both the time and the actual reading. Kappauf, Smith and Bray (1947) exposed panels of 12 dials and had subjects read them in a prescribed sequence under speed and accuracy and under accuracy instructions. Reading time and number of errors for the middle ten dials of each panel were recorded. Typical dials used in these three sets of studies are shown in Fig. 2.

Errors in reading a scale to an exact numerical value have been expressed (1) as a percent of the distance between scale divisions, (2) as an average error computed as arc-distance along the scale, reported either in inches or in the units represented by the scale, and (3) as the proportion of readings in error by more than some arbitrary amount. The first of these measures indicates relative accuracy of interpolation between two scale marks. Results from Grether and Williams' study (1947), in which subjects interpolated to the nearest tenth of an interval, have been plotted to show accuracy of interpolation in Fig. 3. Relative errors of interpolation are, of course, much greater for very small intervals. The minimum relative error was reached at about 0.5 inch per scale division. Weber's law holds approximately over a range of graduation intervals from this point on. Once Weber's law becomes operative, of course, nothing is to be gained in the way of relative accuracy by making divisions any larger. In fact the data suggest that relative accuracy may actually become somewhat poorer with large separation between scale marks. Accuracy relative to the distance between scale marks, however, is not nearly as important for practical purposes as is the problem of minimizing the absolute size of the reading error. The question here is, given a dial of a particular size, how close together should scale marks be placed to provide maximum reading precision?

When absolute accuracy is the criterion, and adequate reading time is permitted, individuals do best when they are given closely-spaced scale marks, such as are used on a slide rule. The results of Grether and Williams' study relating dial diameter, frequency of scale marks, and reading accuracy have been plotted to show absolute accuracy in Fig. 4. Absolute accuracy of reading increased with more closely spaced divisions down to the finest divisions tried, a separation of 5 degrees on a 1-inch diameter dial (0.044 inch of arc distance). In this study Grether and Williams always used a scale running from 0 to 50 (see Fig. 2b), thus minimizing scale-interpretation errors. Kappauf and associates obtained similar results, but found that under accuracy instructions approximately equal numbers of errors were made in reading 1.4- and 0.7-inch dials having graduation marks every 3.6 degrees (0.044 and 0.022 inches of arc distance) and in reading dials of the same diameter with an 18-degree separation between marks (0.22 and 0.11 inches of arc distance). These results were for scales that had marks every 1-unit and every 5-unit respectively. Kappauf and Smith (1948) also found that a small dial graduated from 0 to 600 was read about as accurately when the scale increased by 10's (0.073

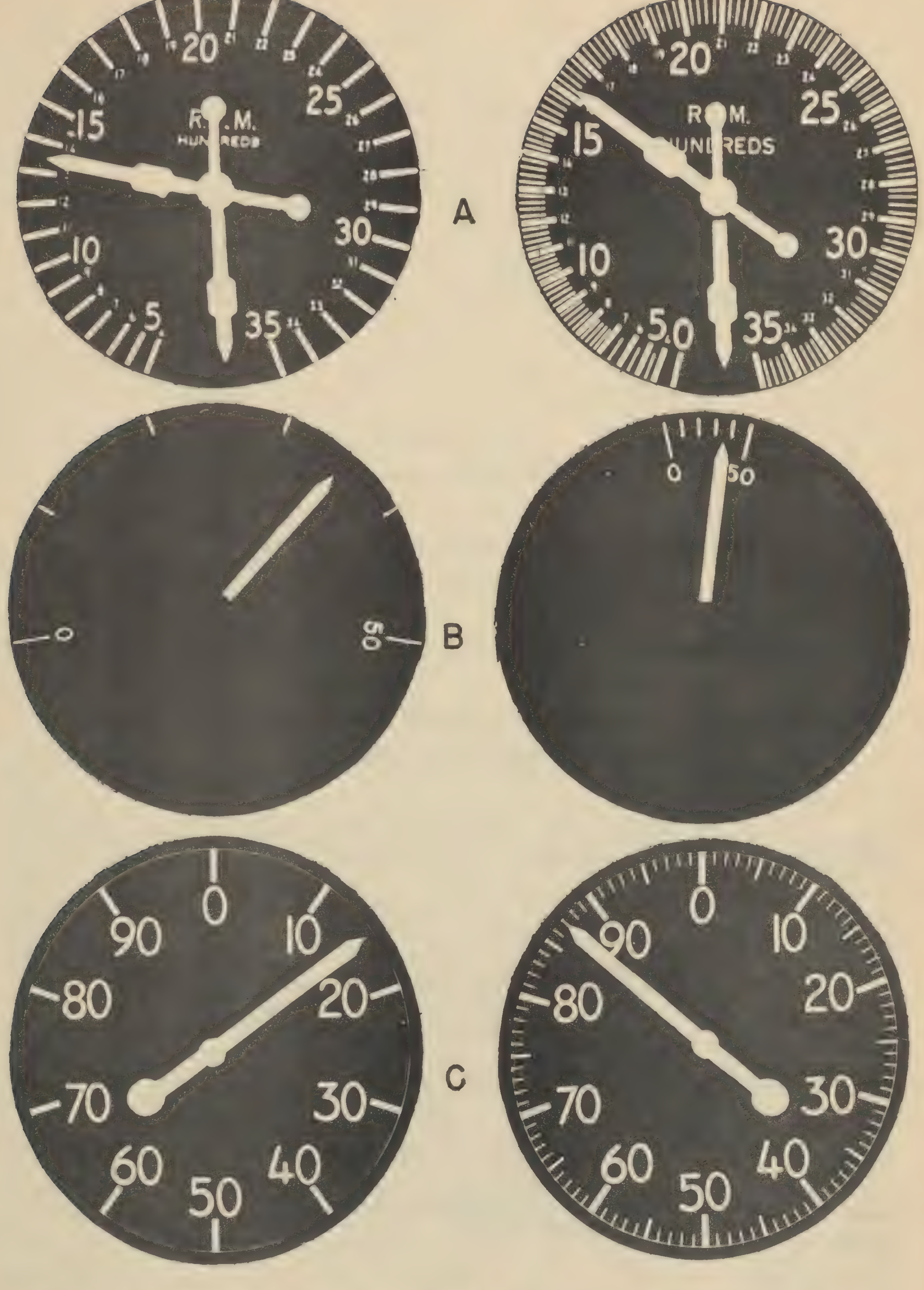



Figure 2. Instrument dials employed in studies of legibility as a function of the spacing between scale markings by (A) Loucks (1944); (B) Grether and Williams (1947); (C) Kappauf and associates (1947).

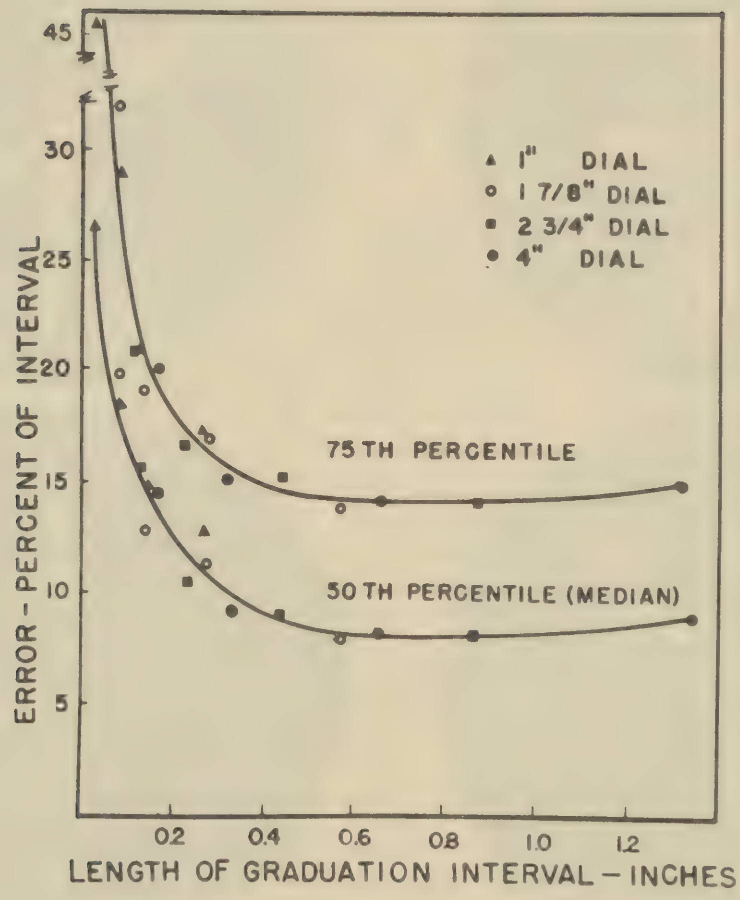



Figure 3. Dial-reading errors for various scale intervals expressed as a percentage of the interval. (From Grether and Williams, 1947).

inch per scale mark) as when it increased by 5's (0.037 inch per scale mark). It appears from the limited data available, therefore, that whereas maximum relative precision in reading circular scales increases as arc distance between scale marks increases, up to a limit in the neighborhood of 0.5 inch of scale separation for instrument-panel (28 inch) reading distance (1 degree of visual angle), maximum absolute accuracy increases as the distance between marks decreases down to a limit at which the scale marks are separated by approximately 0.05 inch (about 6 minutes of visual angle). These specific values are undoubtedly subject to considerable variation with changes in pointer design, lighting, the thickness and length of scale marks, the range of values covered by the scale, and other factors. Maier (1931), for example, reported greatest accuracy when graduation marks were 25 percent as thick as the interval between marks.

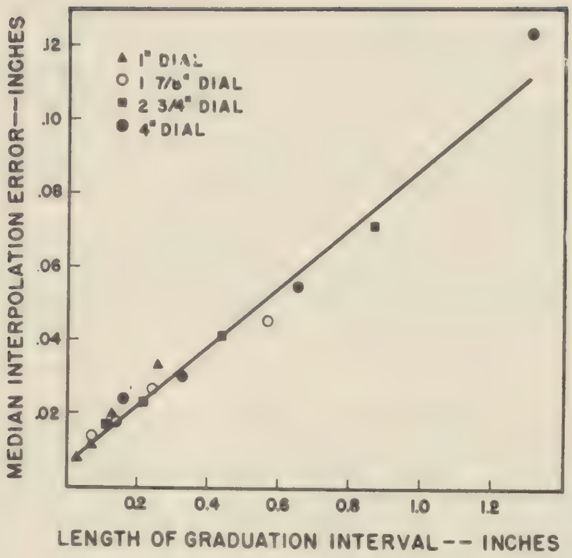



Figure 4. Dial-reading error for various scale intervals expressed as an absolute value. (From Grether and Williams, 1947).

In several instances Loucks (1944, 1944a, 1944c), using a short-exposure technique, found a significant advantage in favor of dials on which some of the scale division marks had been removed. For example, of the two dials shown in Fig. 2-A, with 0.05- and 0.25-inch separation between scales, the one with the larger separation gave significantly fewer reading errors when viewed at near-point reading distance for 0.75 second and also when viewed for 1.5 seconds. Three factors may account for the difference between these results and the results of related studies. First, some of the scale-separation distances that were studied may actually have been considerably smaller than the optimum. Second, the more closely spaced of the two scales had a modulus of 20, while the more open scale had a modulus of 100, and it is known that subjects may make errors of interpretation when using a scale whose modulus is 2, 20, 200, or a similar unit, especially in a situation that requires rapid responses and frequent changes of "set". Third, the time limits of 0.75 and 1.50 seconds probably were somewhat shorter than the time that would have been taken by many subjects had they been allowed to establish their own reading rate. In other words, they may have adopted a "check-reading" attitude, and have dropped out some of the stimulus-response sequences, such as the use of minor scale marks, that occur in the normal quantitative-reading process.

This general line of reasoning is consistent with Loucks' further finding (1944a) that a dial with numerals at every scale division was superior (at the 1-percent level) to one with every fifth division numbered, provided the dial was viewed for as long as 1.5 seconds; but that the opposite was the case (at the 2-percent level) when 0.75 second exposures were used. The reasoning is also consistent with Ford's (1949) discovery that the introduction of fine scaling on a CRT display resulted in an increase in scale-interpretation errors but a reduction in precision errors when readings were made in moderately rapid succession.

Patterns for Signs and Geometrical Symbols. Geometrical figures differ considerably in legibility. Straight lines have been found to be more legible than curved ones (Mackworth, 1944). The triangle, rectangle, and square have been reported to be more easily recognized under conditions of low illumination and in peripheral vision, than circular and hexagonal forms (Collier, 1931; Helson and Fehrer, 1932; Whitmer, 1933).

The use of geometrical symbols and pictographic markers in place of verbal symbols often improves legibility and interpretability. Arrows indicating directions, for example, are better than "right" and "left", since many individuals are momentarily nonplussed when asked to turn to the right or left. Symbols must be chosen carefully, however. For example, it was found (Lauer, 1947) that under average daylight conditions the word STOP on a standard octagonal highway marker could be recognized before the shape was identified, whereas square- or diamond-shaped highway signs could be identified from nearly twice the distance at which the best legend on them could be read.

Optimum Form of Letters. Studies of isolated letters and numerals have employed both visibility and legibility criteria. Results obtained with these two criteria vary considerably. For example, Webster and Tinker (1935) found that American Typewriter type was visible at a greater distance than Scotch Roman type, but that the latter could be read about 5-percent faster. They attributed this to the fixed spacing of typed copy, rather than to the style of individual characters.

There is little difference in the legibility of lower case and of italic type, but most readers favor the former. All-capital printing, however, results in about 12-percent slower reading than lower-case printing (Paterson and Tinker, 1940). In spite of this fact, most decals and emergency instructions on instrument panels and machines are printed in all-capital type.

Studies of the relative visibility of different letters of the alphabet were undertaken as early as 1881 by Javal, a French oculist, who was interested in selecting characters to be used in testing eyesight. Roethlein (1912) carried out a very extensive study of the visibility of isolated characters, using sixteen different type faces. The results of all of her work gave the following average rank order to the various

upper- and lower-case letters of the alphabet, from most to least legible: WMLJI ATCVQ PDOYU FHXGN ZKERBS, and mwdjl pfqyi hgbkv rtncu oxaezs. Tinker (1928) reported that the correlation between results from thirteen studies of the legibility of upper-case letters ranged from -.58 to +.89. For lower-case letters the range was +.48 to +.88. The letter "L" was frequently at or near the top in legibility and the letter "G" was frequently at the bottom. Tinker concluded that the maximum of legibility is represented by the old Roman capitals, which are made up largely of straight lines and sharp angles.

Optimum Form of Numerals. The relative legibility of different numerals depends on the criteria employed as a legibility measure, the style of the numerals, and the figures with which they are associated. The numerals 0, 3, 6, and 9, all of which have curved outlines, are often confused with one another. In most published studies the numeral 7 has been reported to have good legibility and visibility.

In the well-known Snellen test chart, the width of strokes is the same as the width of enclosed white spaces. Recent investigations (Aldrich, 1937; Berger, 1944a; Bartlett, 1947; Lauer, 1947) have shown that a narrower stroke than this is desirable for best visibility. Recommendations for the width of strokes have varied from about 12 percent to 25 percent of the width of the letter or from approximately 8 percent to 17 percent of letter height. Aeronautical standards for white-on-black numerals now specify a line width equal to 12.5 percent of the numeral height for numerals that are over one-eighth inch in height, and a line width of 16.7 percent of the height for smaller numerals. Berger (1944) showed clearly that the stroke-width ratios giving maximum visibility were 7.7 and 12.5 percent of numeral height respectively for white-on-black and black-on-white contrast relations (See Fig. 5). Loucks (1944a) found that for best legibility the stroke thickness should be increased for low brightness levels.

Designs specified for white numerals used on aircraft instruments are shown in Fig. 6-C. Also shown are a set of black numerals developed during the war by Mackworth (1944) for use on air-raid plotting boards, and numerals designed and patented by Berger (1944). Berger's numerals, shown in Fig. 6-A, were designed to give optimum and equal visibility at a distance when printed with white lettering on black, and diffusely lighted from the front. Both Mackworth and Berger made greater use of straight strokes than is customary in commonly-used numeral forms. Most of the slanting lines of Berger's numerals are at 45 degrees to the horizontal.

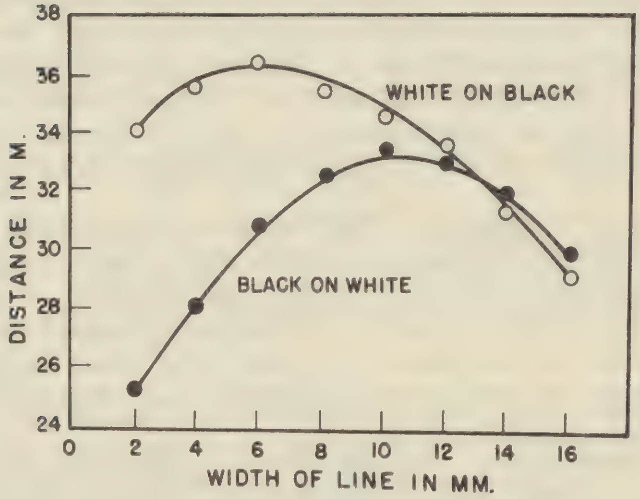



Figure 5. Relation between stroke-width of numerals and the distance at which they could be read for two contrast relations. Note that relatively narrow white-on-black strokes gave optimum visibility. (From Berger, 1944).

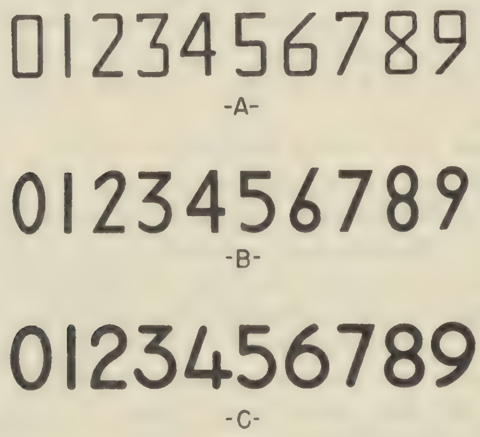



Figure 6. Numeral designs recommended for optimum legibility by (A) Berger (1944), (B) Mackworth (1944), and (C) the Aeronautical Board.

Height, Width and Spacing of Letters and Numerals. The ratio of height to width of letters and numerals has been the subject of a few studies. Lauer (1947) concluded that block letters of equal height and width have best visibility. It is generally agreed that when available width is limited, little or nothing is gained by using very tall characters. Aeronautical design standards, which require a height-width ratio of 1 to 1 for the letter W, a ratio of 1.3 to 1 for A, M, and 4, and a ratio of 1.5 to 1 for all other letters and numerals, appear to represent sound practice.

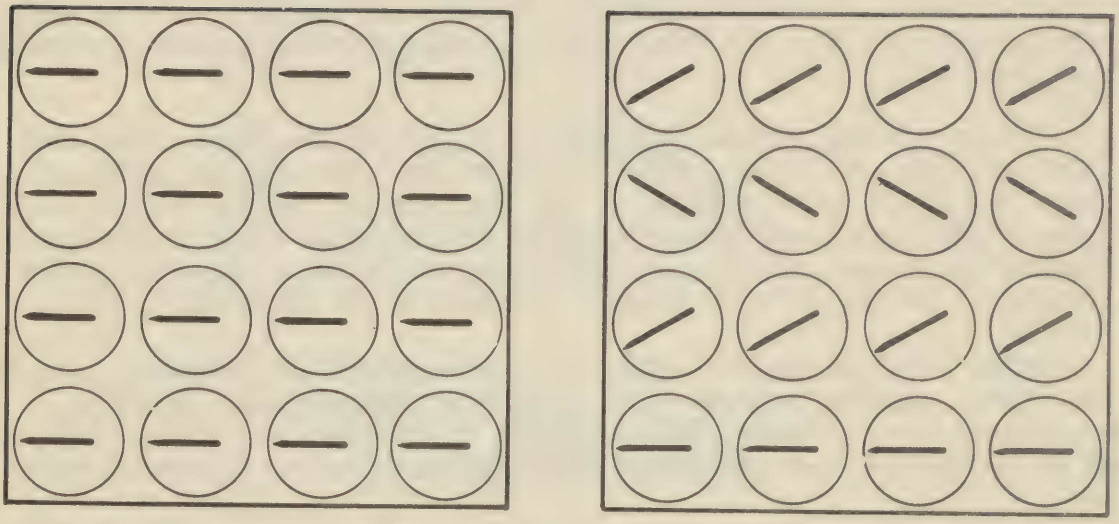
Proper spacing between letters is important for good visibility. A distance between letters equal to about half the average width of a letter was found to be optimum in one case (Lauer 1947). Forbes and Holmes (1939) advocated graded spacing depending on whether strokes of adjacent characters paralleled each other as in NM or VA, one stroke diverged as in VN, or both strokes diverged as in VT or AA.

Other problems involving pattern arrangement of printing, such as line width, spacing between lines, width of margins, and columnar arrangement have been treated in detail by Paterson and Tinker (1940) and by Carmichael and Dearborn (1947) and will not be discussed here.

The role of meaning in the recognition of all types of patterns must not be overlooked. For example, words can be identified more quickly than single letters (Luckiesh and Moss, 1937), and common first names can be read at distances where last names cannot be recognized (Walls, 1943).

Pointer Position Pattern as an Aid to Improved Check-Reading. Warrick and Grether (1948) have shown that a significant gain in speed of check-reading results from patterned arrangement of instrument pointers. They found that if 16 instruments were arranged in a rectangular pattern, with the pointers of all instruments aligned at some cardinal position (such as 9 o'clock), as shown in Figure 7, the entire panel could be checked for deviations and a response switch operated in three-fourths of a second. When the pattern was broken up into sub-groupings of four instruments, response times increased to approximately 1.6 seconds. However, the latter condition still represents a marked gain over most present-day instrument panel arrangements.

Pointer Design. Little work has been done on the improvement of pointer design. Loucks (1944b) using standard black aircraft-instrument dials with 1 1/8-inch pointers, tried painting various lengths of the tip white. A pointer 3/32 inch in width and painted white for nearly its full length was found to give fewer dial-reading errors for short exposure intervals than pointers with 7/16-inch and 9/16-inch white tips. The differences were significant at the 1-percent level, indicating that pointer length is an important variable in legibility. On the other hand, it was found that the effective width of a standard 1 1/8-inch long



| 0.75 | SECONDS PER READING | 1.64 |
|---|---|---|
| 12.8 | PERCENT ERRORS | 16.7 |

Figure 7. Instrument-panel arrangements that gave short check-reading times. Note the horizontal pointer alignment at the 9 o'clock position. (From Grether, 1948a).

pointer could be reduced in width from 3/32 inch to 1/32 inch with no loss in legibility. The narrower pointer actually gave somewhat fewer errors when made to fluoresce under ultraviolet low-level illumination, the difference for twenty subjects being significant at the 2-percent level. This finding agrees with an earlier statement by Maier (1931) recommending that the pointer of stop-watch dials be narrower than the width of the scale marks. A narrow pointer has the further advantage that it covers up a smaller portion of any numeral that happens to lie beneath it.

The amount by which a pointer should overlap the scale, especially when the scale-division marks are of different lengths, is a further problem. Vernon (1946) reported that dial-reading errors increased when the tip of the pointer was more than 0.5 inch from the scale. Parallax resulting from the height of the pointer above the scale is an additional factor that may lead to errors.

Number Preferences. Kappauf (1949) has pointed out that strong preferences seem to exist for certain numbers, and that these preferences carry over into scale-reading tasks, especially if subjects must interpolate between scale divisions. Preferences appear to favor readings of 0, 2, 5, and 8 when interpolation is by tenths. They can be controlled to some extent by training, and by designing displays that require a minimum of interpolation.

Black-on-White Versus White-on-Black Characters. The relative merits of black characters on a light background, versus the converse arrangement, have been variously reported by investigators employing different criteria and different values for the interacting variables. The majority of studies employing visibility criteria have yielded results favoring the use of dark numerals on a bright background (Holmes, 1931; Lauer, 1933; Sumner, 1932; Taylor, 1934). However, Berger (1944, 1944a) found that if strokes of optimum width were used, bright numerals could be recognized under daylight illumination at about 9-percent greater distance by his four subjects than could dark numerals. Starch (1914) and Paterson and Tinker (1931, 1940) found faster reading with black print on white, and Taylor (1934) found that the use of black print led to fewer eye fixations per line than did the less familiar white type.

Two factors that influence the relative visibility and legibility of bright and dark characters are (1) irradiation, and (2) the level of adaptation of the eye.

Meaning and familiarity also play an important role in determining the relative superiority of dark versus bright stimulus objects. The factor of familiarity would be expected to favor black-on-white. Taylor (1934), using a visibility criterion, found that the less meaningful the stimulus material the more marked was the superiority of black-on-white printing, as indicated by the following results:

| Stimulus Material | Percent Superiority of Black-on-White |
|---|---|
| Words in sentences | 11 |
| Isolated words | 17 |
| Nonsense words | 23 |
| Isolated capitals | 24 |
| "i" and "l" combinations | 33 |

Thus it appears that familiarity with a particular stimulus pattern partially cancels out the advantage of the more familiar contrast relation.

In summary, black-on-white has been found superior to white-on-black in most studies of visibility and legibility of single characters and ordinary reading material, but in a few situations the opposite relation has proven to be definitely better. Three important interactions have been demonstrated. These are the width of the stroke, the brightness adaptation of the eye, and the degree of meaningfulness of the stimulus. The final answer to the problem, and explanations in terms of retinal or higher-level phenomena, must await further research.

## Comprehension Problems in the Design of Quantitative Displays

The equipment-design problems considered in the preceding sections have been ones that primarily concerned visual discrimination processes. We turn now to questions that involve the ability to comprehend, interpret, or understand the information presented by visual displays. Errors of interpretation result from many complex and interacting factors, and arise to some extent in the use of all types of displays. They frequently are large in magnitude and serious in consequence. Their elimination often is the most important consideration in the design of a display.

Direct Display of Numerical Data. Quantitative data are commonly displayed either by means of counters or other devices that present numerical symbols directly, or by the position of a pointer on a scale. The advantages of the first of these methods are so obvious as scarcely to require elaboration. Whenever direct-reading displays have been compared with scale-and-pointer combinations it has been found that individuals can obtain numerical information more rapidly from direct numerical displays. The latter are also relatively free from interpretation errors.

Why then does the design of quantitative displays present a problem? It is because displays must often serve multiple functions. They must frequently be designed so that, in addition to being easy to read quantitatively, they can be "check-read" quickly, will show the rate and direction of change of a variable, and will provide the sensory cues necessary for the performance of perceptual-motor tasks. For such multiple-purpose use a pointer-scale type of indication is often superior to a direct-reading numerical display. For example, it was found that the adjustment necessary in changing an indicator to a new bearing could be made more quickly when the cue for the response was the position of a cursor on a scale than when it was the value shown by a counter (Chapanis et. al., 1949).

When scales are read quantitatively two principal kinds of interpretation errors occur -- those made in assigning proper values to scale-division marks, and those made in combining numerical values obtained from several different instruments.

Interpretation of Scales. Vernon (1946) investigated several systems for marking off scales. Errors in reading appeared to be influenced more by the values represented by major scale divisions (the modulus chosen for the scale) than by the values represented by the intermediate scale divisions. Relatively few interpretation errors arose when a scale modulus of 1, 10, 100, etc. was used. An optimum scale design was found to be one with a major numbered graduation mark at each ten, and minor unnumbered division marks at each unit; or else one graduated by 100's and 10's or by some equivalent ratio. In a study of clock dials Grether (1948) found that omission of numerals at any of the hour positions led to an increase in comprehension errors. It can be concluded that all major scale divisions should be numbered if it is at all feasible.

Vernon found further that scales having a modulus of 4 gave many errors. So did those with a modulus of 2 or 20 if the intervening spaces were marked off into fifths. Minor graduations that represented units of 2 were found to be satisfactory when the modulus of the scale was 10 and each major division was numbered. Other studies, however, have revealed that individuals may confuse scales that increase by two's with scales that increase by one's, particularly when mid-division lines change in value from one part of the scale to another, or when different scales are read in rapid succession. Chapanis (1947), using a polar-coordinate presentation, had observers interpolate between range rings when values of one-, two-, etc. up to ten-thousand yards were assigned to each ring. Readings with the 1000, 2000 and 10,000 scales were most accurate; those with the 3000 and 6000 scales were least accurate

Scales that increase from right to left, or counterclockwise, are particularly susceptible to interpretation errors. An error common to this type of scale is that of reading in the wrong direction from a numbered graduation, such as reading 21 in place of 19 or reading 22 in place of 18. Christensen (1948) found that the use of a "staircase" scale, on which the lengths of minor scale graduation marks increased in proportion to their numerical values, reduced the frequency of this particular error significantly. Wherever possible, however, right-to-left or counterclockwise scales should be avoided.

Interpretation of Instruments that Indicate Over a Wide Range of Increments. Instruments can be arranged in a continuum with respect to the number of discriminable differences that they provide. At one end of this continuum are all-or-none indicators, such as warning lights and "stop" or "go" signs, which provide only two categories of information. At the other end are displays, such as watches, that can be read in thousands of discrete steps. A watch, for example, if read to the nearest second, indicates a total of 43,200 different time-steps during a 12-hour period.

It is obviously not feasible, because of the length of scale that would be required, to indicate variables such as time by means of a single pointer moving along a continuous scale. Several variations of the simple pointer-scale principle can be employed, however, to overcome this limitation. Among these variations are ones involving the use of single dials with several concentric pointers, e.g. watches with sweep second hands, the use of several one-pointer dials with different sensitivity, e.g. gas, water, and electric meters, and the use of long scales affixed to moving tapes. Most of these devices use broken or divided scales that require the reader to combine data obtained from several sources. They all are subject to errors of comprehension. It will be recalled (see Table I) that the type of error described most frequently by aircraft pilots was one of misreading multiple-pointer instruments. The aircraft altimeter, a multiple-pointer instrument, was often read with an error of exactly 1000 feet. Bray (1948) reports that one of the most serious errors made in directing artillery fire during World War II was one of exactly 100 mils. Both of these errors occurred because observers had to make a gross and then a vernier reading, in one case from separate moving pointers, in the other case from separate moving scales.

Following up the results of the critical-incident study described earlier, Grether (1949) investigated nine different instrument designs for presenting wide-range quantitative data in an effort to find an improved altimeter design. He used printed tests on which subjects wrote down their readings. The nine designs are shown in Fig. 8. Time and error scores obtained from 97 USAF pilots and 79 college men without pilot experience are also shown. In spite of the wide experience differences between trained pilots and college men, almost identical results were obtained from both groups, The relative magnitude of average time scores and of average error scores associated with each instrument is essentially the same for both groups of subjects. This is revealed by the fact that the correlation between speed scores of the two groups was .99 and between error scores was .95. These correlation coefficients were computed by first determining average scores for each group of subjects on the nine instruments, and then computing the correlation between scores for the pilot and college groups with N equal to 9 instruments. It is obvious that the variance in group performance attributable to designs was much greater than the variance attributable to years of experience in using particular instruments.

Errors in reading the conventional three-pointer altimeter were classified into seven categories. These categories are given in Table III together with the frequency counts for each in the pilot and college populations. Specific errors illustrating each category are shown in Fig. 9. In only two of the seven types of errors was the frequency substantially less for the more experienced group. This finding provides further evidence that from a practical viewpoint design often is relatively more important than training as a factor in instrument reading.

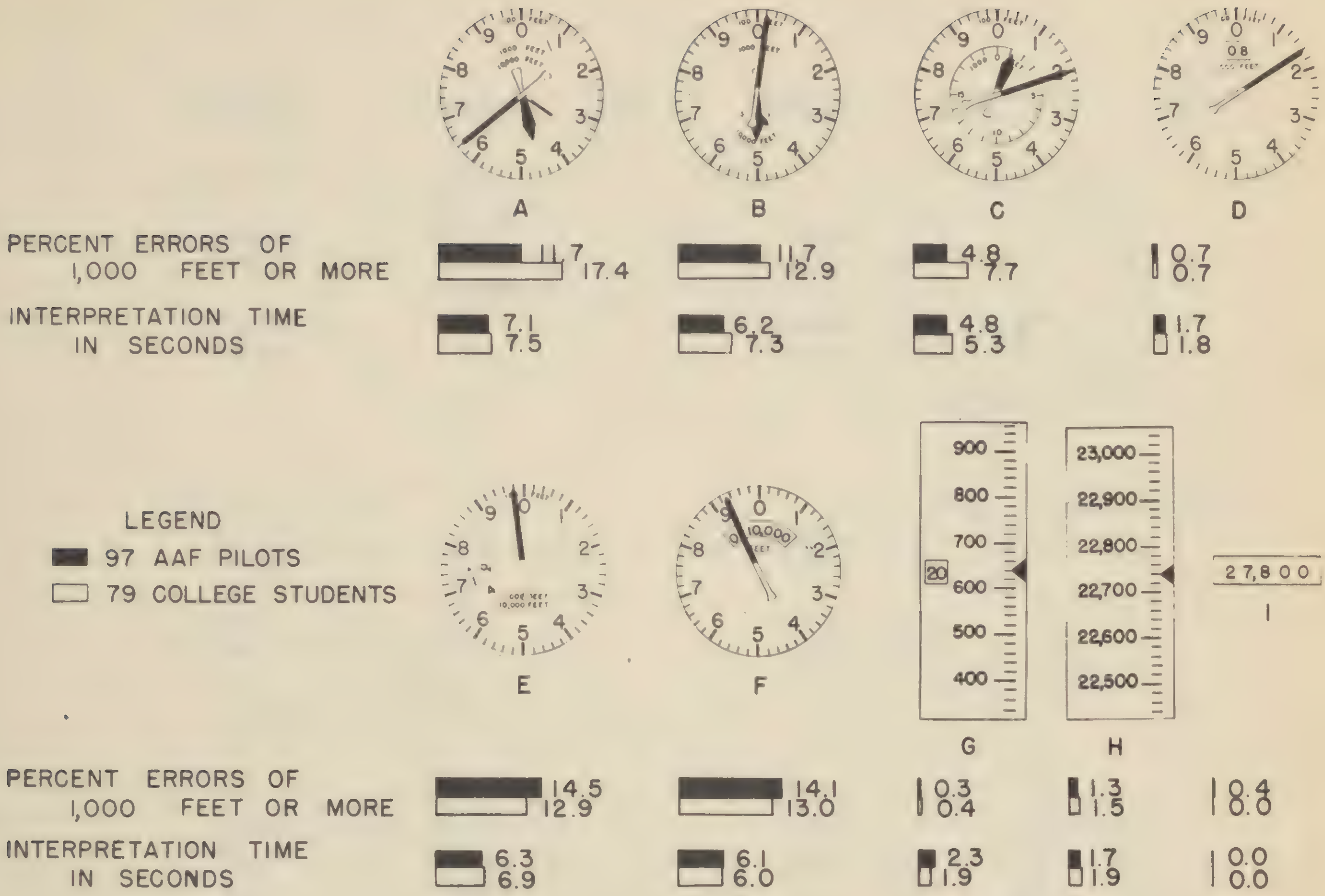



Figure 8. Nine instrument designs for indicating quantitative values over a wide range. Some results are given for speed and accuracy of reading by two groups of subjects differing widely in experience. (From Grether, 1949).


Figure 9. Types of errors made in reading a three-pointer instrument. (From Grether, 1949).

TABLE III

Classification of Errors Made in Reading a Multiple-Pointer Instrument*

N = 97 USAF Pilots and 79 Male College Students
(See Figure 10 for examples)

| Type of Error** | Percent of Errors: Pilots | Percent of Errors: College Men |
|---|---|---|
| A. Misinterpreting the value of a scale division | 5.8 | 7.1 |
| B. Interchanging numerals | 4.0 | 5.5 |
| C. Reading a value from a major scale division before it is reached | 4.4 | 3.7 |
| D. Omitting the value indicated by one of several pointers | 0.3 | 2.3 |
| E. Reading a value from a major scale division after that division has been passed | 0.3 | 2.3 |
| F. Repeating the value indicated by a pointer | 1.0 | 0.8 |
| G. Other complex, unclassified errors | 0.9 | 1.5 |

* Subjects read a sensitive aircraft altimeter, on which three concentric pointers represented hundreds, thousands, and tens of thousands of feet respectively.

** Error descriptions have been modified slightly from those used by Grether (1949).

In the study under discussion the fastest and most accurate quantitative readings were made from the direct numerical display. The two designs that permitted the next best performances were the one combining a single pointer and a counter, and the one representing a moving tape. These latter designs have many practical applications. In these practical situations choice between designs will depend on considerations in addition to those of speed and accuracy in quantitative reading -- considerations such as suitability for "check-reading" and for quick detection of rate of change or direction of change of a variable.

Graphs and Tables. Relative speed and accuracy in obtaining quantitative values from graphs, double scales, and tables are dependent upon factors that are similar to the ones discussed in the preceding sections. Reading a graph is similar in many respects to interpreting the value shown by a pointer on a scale. Table reading resembles the reading of a counter or other direct numerical display, although at times it may also require interpolation.

Carter (1947) had subjects work identical problems using various kinds of tables and graphs. The type of problem was found to interact significantly with the type of display. Problems requiring no interpolation were in all cases solved more quickly by the use of a table, regardless of the complexity of the numerical function. Problems requiring single or double interpolation, on the other hand, were solved much more rapidly by the use of graphs. The differences in all cases were large and highly significant. Results for the function $y = x^2/c$, with c taking on four values, were as follows:

| Type of Problem | Problems Solved Per Minute | |
|---|---|---|
| | Graphs | Tables |
| No interpolation | 5.5 | 11.32 |
| Single interpolation | 4.4 | 2.6 |
| Double interpolation | 3.8 | 0.8 |

Note that interpolation problems required very little more time than non-interpolation problems when a graph was used, but required 14 times as long as non-interpolation problems when a table was used.

Essential Characteristic of a Good Quantitative Display. The experimental results reviewed in the preceding section support the hypothesis that the probability that an error in comprehension will occur increases directly in proportion to the number of separate

stimulus-response operations required before the value shown by a quantitative display can be determined[1]. Such an hypothesis has already been proposed to account for the differential effect of speed-up conditions on the legibility of instrument scales. It also offers a plausible explanation for such experimentally-determined facts as the superiority of counters over scale-pointer combinations, the superiority of uniform over logarithmic or other non-linear scales, the advantage of scales having a modulus based on even units, tens, hundreds, or thousands rather than on intermediate values, and the inferiority of instruments that require synthesis of information from several different sources. Grether (1948a) has suggested that absolute errors in interpolating between major scale-division marks often increase inversely with the number of intermediate marks, while errors of comprehension often increase directly in proportion to the number of sub-divisions. Ford (1949) has reported experimental evidence from studies of radar-scope scaling methods showing that this happens. In a good all-purpose display we must compromise between these two opposed considerations, remembering that comprehension errors are usually large, while interpolation errors are usually small.

## Comprehension Problems in the Design of Displays for Indicating Spatial Relations and Changes in Magnitude

The advent of the air age, with the tremendous speeds made possible by air travel, has made the display of spatial information of critical importance to aircraft pilots, traffic controllers, and many other machine operators. The designing of displays to represent spatial relations such as direction, distance, and relative motion, however, is one of the most complex problems in engineering psychology.

Numbers can be used to represent altitude, distance, and other relations, of course, but there are many situations in which an overall qualitative picture (a "situation" or "pictorial" display) is needed rather than sets of numbers. Displays are needed that will provide cues for the direct perception of spatial relations and for the performance of continuous perceptual-motor tasks, such as the flying of an aircraft without any vision outside the cockpit.

The Representation of Spatial Relations. At first thought it might seem that an ideal display of spatial relations would be one that exactly reproduced all the cues normally utilized by an individual in space perception. Such a display would find a great many uses. It would be difficult, if not impossible, however, for

1. A specific theory relating error-frequency and number of S-R connections was proposed by W. F. Grether in a staff meeting of the Psychology Branch, USAF Aero Medical Laboratory.

engineers to devise such a complete reproduction of nature. And even if a complete situation display were provided, the unaided human eye in some situations would not be able to make all the necessary discriminations, and therefore would have to be given supplemental symbolic information. An automobile driver, for example, relies on his speedometer for an indication of speed in preference to the impressions that he gains from observing the rate of movement of objects along the road.

Two solutions are possible. One is to provide both situation displays and supplemental quantitative displays. The other is to find substitutes for the cues available during normal vision, substitutes that facilitate rapid comprehension of essential spatial relations, and at the same time provide more precise information than is gained through unaided vision. One important research task is the determination of how far it is possible to go in using schematic or semi-pictorial displays that permit relatively precise reading, without serious impairment of orientation ability. One aspect of the problem has sometimes been stated as that of determining whether a schematic display gives a "natural" indication.

The terms "natural" and "unnatural" are confusing in this context because of the dual reference to ease of discrimination and to unlearned modes of interpretation. This confusion can be avoided by substituting the concept of a commonly observed behavior pattern or population stereotype. The latter concept implies only the notion of frequency of occurrence with no implication that the response is learned or innate.

It has been assumed by some writers that even if an individual greatly overlearns a response that is contrary to an earlier habit, he will frequently revert to the population stereotype under the stress of an emergency. There is no experimental evidence to show that this hypothesis holds for the interpretation of instruments or the operation of controls, although anecdotal reports appear to support it. It has also been assumed that the level of performance reached after extensive practice in a skill will be higher if the habits constituting the skill agree with population stereotypes. There are many well known exceptions to this hypothesis. Few indeed are the "natural" athletes, for example, who do not improve in skill by changing their style under the guidance of an expert coach. It has been pointed out further that training time can be minimized by taking advantage of stereotyped response patterns. Of the several reasons for designing displays to agree with stereotyped modes of interpretation, the advantages with respect to economy of learning appear to be most important.

Experimental Determination of Population Stereotypes in Responding to Directional Cues. Population stereotypes in responding to directional cues have been determined for only a few of the possible combinations of controls, displays, sets, figure-ground relations, and operator tasks. Several studies of direction-of-motion stereotypes have been carried out at Cambridge University (Vince, 1944; Vince and Mitchell, 1946; Mitchell, 1947, 1948). The motions of displays and controls used in these studies were those made by pivoted pointers and levers. Responses were made to discrete stimuli appearing in rapid succession. Considering the case in which the operator tried to cause the display to move upward, it was found that the control movements from most to least effective were upward, forward, right or left, backward, and downward. Similar results were obtained when the operator's task was complicated by requiring him to carry on two concurrent activities. In general, the effect of direction of motion relationships was less marked in continuous than in discontinuous tasks, and less marked for the preferred than for the non-preferred hand. Experimental results from one study are summarized in Table IV.

Fitzwater (1948), using successive short work periods and carefully matched experimental groups, discovered that when a clockwise movement of a control lever resulted in clockwise rotation of a display pointer (in the 12 o'clock dial sector) a significantly higher score was obtained in a continuous compensatory-pursuit task than when the same control movement caused a counter-clockwise rotation of the pointer.

Population stereotypes in the operation of a variety of rotary controls in response to both linear and circular displays have been studied by Warrick (1947, 1947a). In one experiment responses were recorded while subjects were attempting to move the light on a display to a center position. No fixed movement relation was imposed between controls and indicators, and all responses were rewarded. This was accomplished by the use of an apparatus that caused the display to move toward its center position whenever its associated control was rotated, regardless of the direction of rotation (see Fig. 10). It was found that when a linear display was located directly above a rotary control, the typical individual turned the control clockwise to move the display to the right and counterclockwise to move it to the left. In most other control-display arrangements subjects moved the side of the rotary control that was adjacent to the linear display in the same direction as that in which they wanted the display to move. The total number of clockwise responses, however, exceeded the number of counterclockwise responses. Similar direction-of-motion stereotypes were recorded by Carter and Murray (1947) for responses made in controlling the movement of a spot on an oscilloscope tube.

TABLE IV

Relative Efficiency of Different Movements of a Control Lever in Response to an Up-or-Down Display Movement*

(N = 10 subjects for each relationship)

| Relation Between Control-Lever and Marker | Average Number of Errors During 60 Trials: In a One-Hand Task | Average Number of Errors During 60 Trials: In a Two-Hand Task |
|---|---|---|
| 1. Upward control movement caused marker to move upward. | 3.0 | 4.2 |
| 2. Forward (away from body) control movement caused marker to move upward. | 4.5 | 5.3 |
| 3. Rightward control movement caused marker to move upward, combined with results obtained when a leftward control movement caused marker to move upward. | 7.0 | 9.2 |
| 4. Backward (toward body) control movement caused marker to move upward | 6.8 | 11.1 |
| 5. Downward control movement caused marker to move upward | 8.0 | 11.9 |

*From Mitchell, 1947

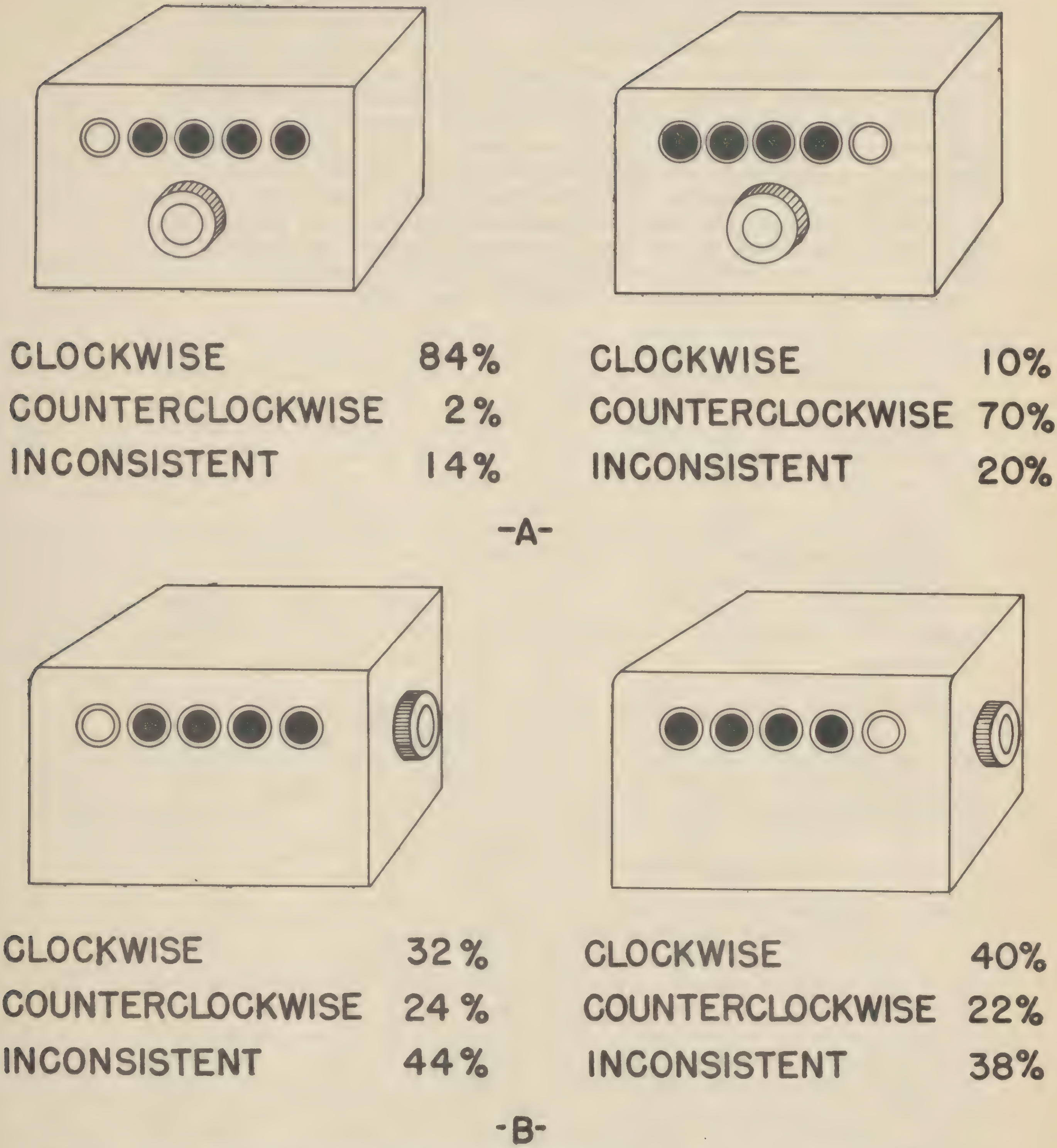



Figure 10. Population stereotypes for movements made in centering a light on a linear display by means of a rotary control. In arrangement A the control was mounted on the same plane as the display; in arrangement B the control and display were in different planes. The light could be centered by turning the knob in either direction. The directions actually used by the subjects are tabulated. Note the preponderance of clockwise responses. (From Warrick, 1947).

When controls and their associated displays were located on panels at right angles to each other, as shown in Fig. 10-B, many individuals gave ambiguous responses, i.e. they reacted to the same stimulus sometimes with a clockwise response, sometimes with a counterclockwise response. When displays were made in the shape of an arc, the subjects adjusted the controls more rapidly when they were required to rotate them clockwise in order to move the displays in a clockwise direction around the arc. For example, if it were desired to move the light on the display shown in Fig. 11-A to the right (counterclockwise), the edge of the control nearest the display was moved to the left (counterclockwise) by most individuals. However, performance was not as efficient with this arrangement as it was with that shown in Fig. 11-B.

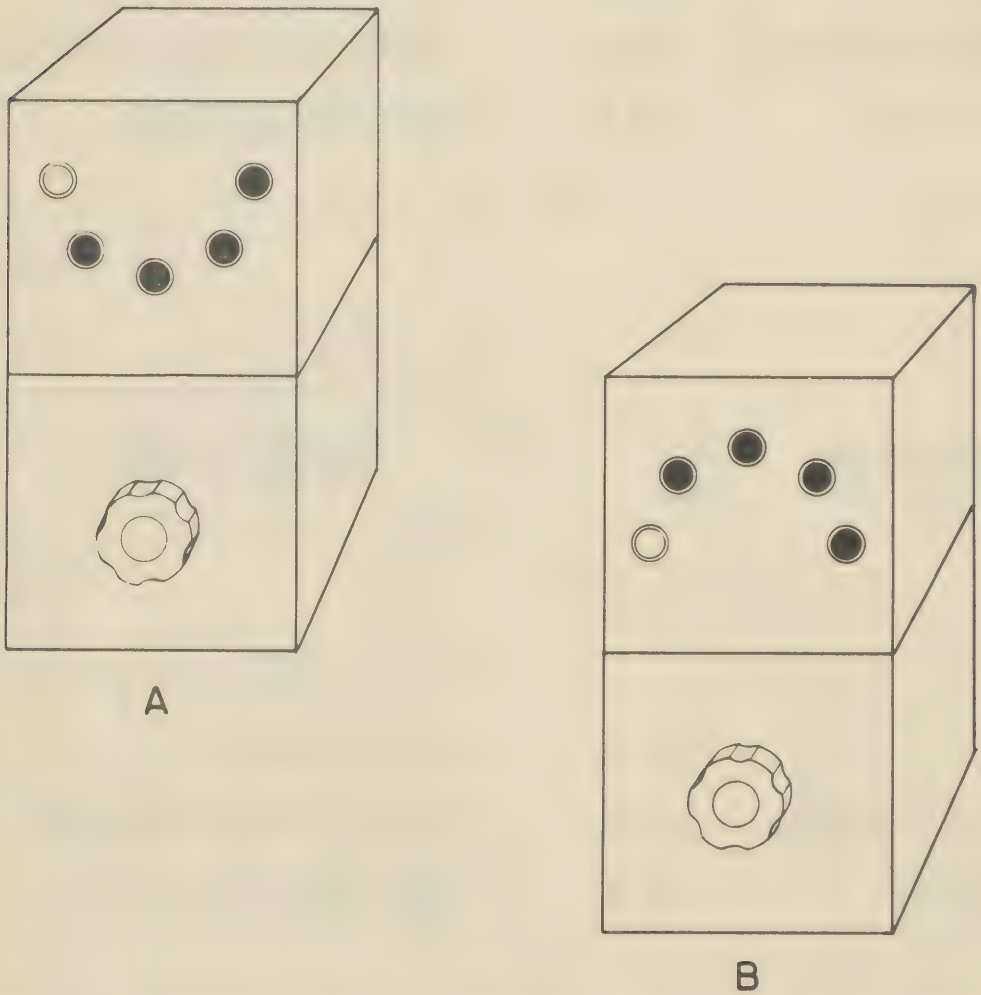



Figure 11. Apparatus used in studying the efficiency of subjects in adjusting different arrangements of rotary controls and semicircular displays. In each instance performance was most efficient when a clockwise control motion resulted in lighting the lights on the display in a clockwise sequence. (From Warrick, 1947a).

The Role of Figure-Ground Relations in Determining Responses to Directional Cues. Responses to directional cues are determined in part by configurational properties of the total visual field. Responses may depend upon whether the control is located to the right or left of the display, whether the control and display movements can be projected onto the same plane in space, whether control and display movements are rotary or translatory, and upon the dominance of various parts of the visual field. Duncker (1939), for example, showed that if a point of light is observed within an oscillating rectangular frame observers usually attribute motion to the light rather than to the frame and report that the direction of motion is opposite to that which really exists.

It is known that apparent figure and ground relations sometimes become reversed. Such a reversal may occur when an aircraft pilot switches from "contact" to "instrument" flight. As long as the pilot can see the earth, he usually perceives his own aircraft to be banking, climbing, or diving with respect to the stationary earth below, i.e. he interprets movement cues in an "external reference" framework and perceives his own aircraft as figure. However, as soon as outside vision is excluded, the visible parts of his own aircraft, such as the instrument panel and cockpit enclosure, usually become the fixed background with reference to which the small moving parts of the instrument displays appear as figures.[1] He now responds in terms of an "aircraft reference" principle. An obvious explanation for this reversal is in terms of familiarity and of relative size.

Several observers have reported figure-ground reversals when watching the ground from a banking aircraft (MacLeod, 1940; Moore, 1940; Webster, 1940). When the earth was viewed through a near-by window, so that it subtended a relatively large visual angle, the aircraft was perceived to be in a bank; however, when a relatively small area of the earth was seen through a distant window, the aircraft was perceived to be level and the earth tilted.

The original flight attitude indicator, which was the prototype of most attitude instruments still in use, was designed with an "artificial horizon" bar that remained parallel to the earth's horizon during the roll of the aircraft. It was thought that this use of the external-reference principle would give the pilot the impression that he was actually looking at the horizon and thereby reduce his "mental effort" (Poppen, 1936). Such an instrument is illustrated in Fig. 12. The external reference principle has also been followed in indicating the dive angle of submarines. It turns out that if the horizon bar is perceived as figure (instead of as part of the background) and is responded to in accordance with the

1. Some experienced pilots, however, state that they have succeeded in preventing this reversal from taking place.

population stereotype, the pilot or the submarine crewman will move his control in the wrong direction (make a "reversal" error) and aggravate the existing deviation from level flight. Pilot reports show that this frequency happens during the early stages of flying training (Fitts & Jones, 1947a). Similar errors have been reported by the men operating submarine diving controls. Furthermore, two


Figure 12. An "artificial horizon" instrument used to give orientation information to pilots. The indication shown is that of a diving turn to the left. The long white line is a gyro-stabilized bar that represents the position of the earth's horizon.

experimental studies carried out in England and the United States (Browne, 1945; Loucks, 1947) agreed in showing that novices make fewer errors in responding to an artificial horizon type instrument that must be interpreted in accordance with the aircraft reference principle than to an indicator that must be perceived as a part of the background and interpreted in accordance with the external-reference principle.

Set and Change of Set in Responding to Directional Indications. The important role of "set" in the interpretation of directional cues can be illustrated by one of the conditions investigated by Warrick (1947a). Subjects alternately adjusted two rotary controls, each of which governed a related semi-circular display. When clockwise rotation of the controls resulted in clockwise movement of the controlled objects performance was superior to that recorded when clockwise control movements resulted in counterclockwise display movements. However, when a mixed arrangement was used, i.e. when a change of set was required between successive responses to the two controls, overall performance was inferior to that recorded under either of the two uniform conditions. Interestingly enough the greater number of errors in the change-of-set task was made in adjusting the control that operated in accordance with the population stereotype. Apparently the necessity for repeated change of set caused greater disruption of the more habitual response than of the less well established one (perhaps because subjects were concentrating on the set required by the non-habitual response). An obvious conclusion from this finding is that all controls that must be operated in a rapid sequence should conform to a uniform direction-of-motion principle.

It must not be overlooked, however, that certain shifts in set can be made with little or no confusion if the total situation is favorable. For example, an individual who knows he is steering with a wheel seldom experiences any difficulty when he shifts his hand from the top to the bottom of the wheel even though this means reversing his control movements.

Error Versus Correction Information. It has been proposed that a display should indicate how to correct an error rather than indicate the nature of the error itself. This proposition implies that the less thought and deliberation required in organizing a response the faster will be the reaction and the fewer the errors, and that response processes are simplified when attention is directed to the movement to be made rather than to the error to be corrected.[1] This hypothesis is not subject to direct verification. We can measure response time and errors, but not the complexity of mental processes. The hypothesis appears to be contradicted by the available data on population stereotypes. Most individuals habitually respond to the movement of an indicator by executing a movement

1. This distinction is not comparable to that traditionally made between sensory and motor set.

in the opposite direction. The typical individual, therefore, apparently interprets a display as if it were an indication of error and responds to it as if to drive the error in the opposite direction. This fact is accepted in most display situations. As a result of long experience it has been decided that the Landing Signal Officer on an aircraft carrier, for example, should hold his signal flags up when the approaching pilot is too high. Displays in most cases should indicate the direction of the error, not the direction of the movement to be made in correcting it.

Ambiguity of Directional Cues from Circular Displays. Rapid and accurate directional responses cannot be made equally well to indications from all sectors of a rotary display. Warrick and Grether (1948) studied the ability of subjects to check-read panels of 16 circular instruments and to interpret as "too much" or "too little" the deviations shown by any instrument that deviated from a "normal" reading. When the "normal" pointer position was at 9 o'clock on the dial, performance was superior to that recorded when the "normal" position was at 3 o'clock. This was true whether subjects were required to respond by moving a switch up to show that they knew the indication was too high, or by moving it down to show that the indication should be decreased.

Fitts and Simon (1949), utilizing a compensatory dual-pursuit apparatus, required subjects to keep the pointers of two instruments centered by operation of two rotary controls. Pointer alignments at the 12, 3, 6, and 9 o'clock positions were compared. In the case of both horizontal and vertical separation of the two circular instruments the 9- and 12-o'clock positions were found to give consistently higher performance scores than the 3- and 6-o'clock positions. Likewise, Connell and Grether (1948) and Long and Grether (1949) found a greater number of errors in verbal reports of the direction of change represented by a pointer movement when the movement occurred in the right or bottom quadrants of a circular dial than when it took place in the left or top quadrants. The inferiority of the right and bottom quadrants as revealed by such findings is probably due to the conflict, in this part of a circular dial, between the principle of up or right to indicate an increase, and the principle of clockwise to represent an increase.

Moving Pointer Versus Moving Scale. A change in the magnitude of a value can be shown by movement of a pointer, by movement of a scale behind a fixed lubber line, or by simultaneous movement of both pointer and scale. The problem of designing a compass for use on a vertical instrument panel will serve to illustrate some of the directional ambiguities that are met in connection with each type of display.

A scale that moves behind a window or fixed lubber line permits the operator always to look at the same point in making a reading. An instrument designed in this way cannot be check-read easily, however, because the numbers on the scale must always be read before a response can be made. Furthermore, if scale values increase in a clockwise direction, then the scale must move in a counterclockwise direction in order to show an increase; whereas if the scale is designed so that it rotates clockwise to indicate an increase, then values on it must increase in a counterclockwise direction. Neither alternative is a satisfactory one.

It is easy to check-read a moving-pointer instrument when the pointer is in the left and upper parts of the dial, but when the pointer is in the bottom or right quadrants reversal errors may sometimes occur, as was shown in the preceding section. Long and Grether (1949) and Loucks (1949), assessing verbal and motor responses respectively to moving dials, moving scales, and moving pointers, agreed that a moving pointer in the upper half of a compass-type dial results in the fewest ambiguous responses.

Grid and Coordinate Systems. Two-dimensional coordinate systems are used on maps, graphs, television screens, and many other projection surfaces. Rectangular and polar coordinates are most common, but other systems are possible. A few of the many possible systems are shown in Fig. 1. Few studies have been made of the ability of individuals to interpret these various coordinate systems.

Compasses and terrain displays can be azimuth-stabilized, i.e. north can be made to appear always at the same point, such as the top; or they can be heading- or course-stabilized, i.e. the direction in which the reader is traveling or looking can be made to appear always at the same point, such as the top. Maps can be used with north at the top, or they can be rotated as the user turns. The advantages of the two systems with respect to the maintenance of orientation are still not clearly defined. Loucks (1949) found that novices became more seriously disoriented when using a rotatable map with a fixed-scale compass indicator than when using a fixed map. Much may depend on which principle one has been trained to use, and on whethen an immediate motor reaction or a deliberate intellectual response is required.

Variations in Magnitude. It is generally accepted that an increase in magnitude or a change from "off" to "on" should be represented by movement of an indicator or of a control device in a clockwise direction if motion is rotary, or if motion is translatory, then by movement of the display or control upward, forward or to the right. Although little experimental work is available on this topic, common practice seems to be sound. Clocks, thermometers, speedometers, and nearly all types of scales follow this convention.

The directions employed in control movements are not as well standardized, however. Controls that follow opposite principles can be found on radios, stoves, locks, and many other common devices. These exceptions often lead to confusion. Switch positions on central telephone switchboards and in electrical sub-stations, on the other hand, are standardized. Here one of the most useful principles is the use of the center or neutral position for "off".

Essential Characteristics of Good Qualitative Displays. A satisfactory qualitative display should conform to population stereotypes. The required interpretation should be in harmony with the configurational structuring of the environment in which the display is to be used. The display should also conform to the sets required in interpreting related displays. The movement of a display should correspond wherever possible to the direction taken by the error and not the direction appropriate for corrective action.

Undoubtedly these requirements reflect the nature of the processes by means of which men orient themselves. In the design of qualitative displays, as was true for quantitative ones, the best display is one in which the fewest intermediate processes must intervene between the stimulus and the appropriate response. This topic is too complex, and too little is known of the processes involved in maintaining orientation, to permit formulation of any general theory to guide display design. A theory of spatial orientation is needed that will synthesize the various findings in this area, and provide a basis for a deductive approach to future design studies.

## AUDITORY DISPLAYS

An on-off or pulsed signal, such as that produced by a policeman's whistle, is the simplest type of auditory display. It is possible, however, to transmit quite complex information by means of a temporal pattern of these on-off signals. In fact, high-speed "flip-flop" circuits and a binary digital system offer perhaps the most efficient means of transmitting complex information at extremely high speed. Information may also be transmitted by amplitude, frequency, phase, or some other type of modulation of a carrier signal. Auditory signal systems make use of all of these possibilities.

Auditory signals almost always are accompanied by other sounds that carry no useful information. Only in such places as anechoic research rooms is an individual's environment free from this unwanted noise. Signal-to-noise ratio, or the ratio of the amplitude of information-carrying signals to that of noise, is a commonly used measure of the amount of noise interference present. In terms of statistical concepts of

communication theory, noise level can be thought of as the probability that any discriminable signal does not represent transmitted information, but is simply a fluctuation in the background of random noise. Because of the pervasiveness of unwanted sounds, the following discussion will deal primarily with auditory discrimination in the presence of noise.

## Auditory Signal Systems

As a means of introducing some of the design factors that influence signal intelligibility, it will be of advantage to take as an example a particular signal system. The low-frequency radio range will serve this purpose.

Discrimination of Aural Radio Range Signals. Radio range signals are produced by bi-directional radio signals of 1020 cps. Each signal is interlocked with the other in such a way that if their signal strengths are equal, a steady tone is heard. American radio ranges use the code letters A (dot-dash) and N (dash-dot) to identify the two interlocking signals. Pilots fly at assigned altitudes along the right edge of an air lane at a position where they are just able to detect the A or N signal. They are separated from aircraft going in the opposite direction by a zone of silence the width of which is inversely proportional to their ability to discriminate auditory signals.

Signal-to-noise ratio is one of the principal factors determining the discriminability of auditory signals. In one study (Flynn, et al., 1945) the minimum intensity difference that permitted discrimination between A and N signals was found to vary from about 0.5 db at a favorable signal-to-noise ratio of 50 db, to about 2.5 db at an unfavorable ratio of -10 db. The optimum signal intensity, however, varied somewhat with the level of background noise.

The meaning of such data for a pilot flying a radio range is represented graphically in Figure 13. Under the ideal conditions of no static, a pilot with normal hearing should be able to fly a course that would deviate approximately 1.5° from the center of the beam. This course is represented by dotted lines. At 150 miles from the range station he should be 4 miles off course. The solid lines in Figure 13 represent the extent to which he would be driven off course by the presence of static. Thus at 150 miles with 50 $\mu$v static he would have to be 16 rather than 4 miles off course in order to be sure that he was flying on the right side of the beam.

If a noise source affects the electrical circuit of the signal system, then all that the operator can do in order to minimize its effect is to adjust the gain to an optimum value for that condition. On the other hand, if the noise source is external to the receiver,

he can turn up the gain, thereby increasing the signal-to-noise ratio at the ears, then reduce the over-all sound level at the ears to an acceptable loudness value by wearing ear plugs. This gives a considerable improvement in the ability to discriminate signals.

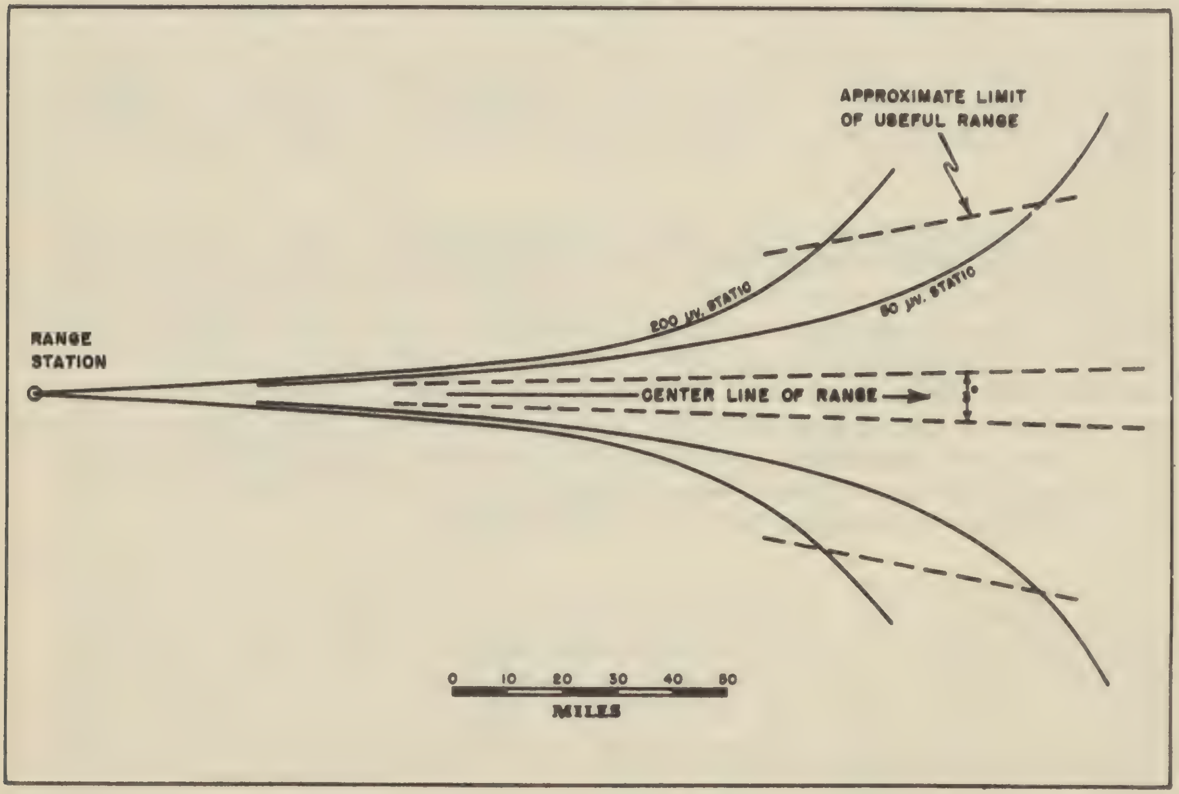



Fig. 13 Map Showing Effective Width of Radio Range in Presence of Static

Selective Signal Circuits. The specific characteristics of information-carrying signals cannot be predicted. There are, however, certain statistical characteristics of meaningful signals by means of which, on the average, they can be distinguished from random noise. Such differences between signals and noise, considered in relation to the differential sensitivity of the ear for different stimulus combinations, can form the basis for a certain amount of noise reduction. For example, it has been reported (Flynn, et al., 1945) that a suitable filter

permits a pilot to follow radio range signals in approximately 10 db more static than is possible without the filter (see Figure 14). When a circuit is to be used for both code and voice reception, the best practice is to provide for the optional use of a band-pass filter for attenuating frequencies other than the code frequency when it is desired to listen for code sounds, and a narrow band-elimination filter for attenuating the code sound when it is desired to use the system for voice communication.

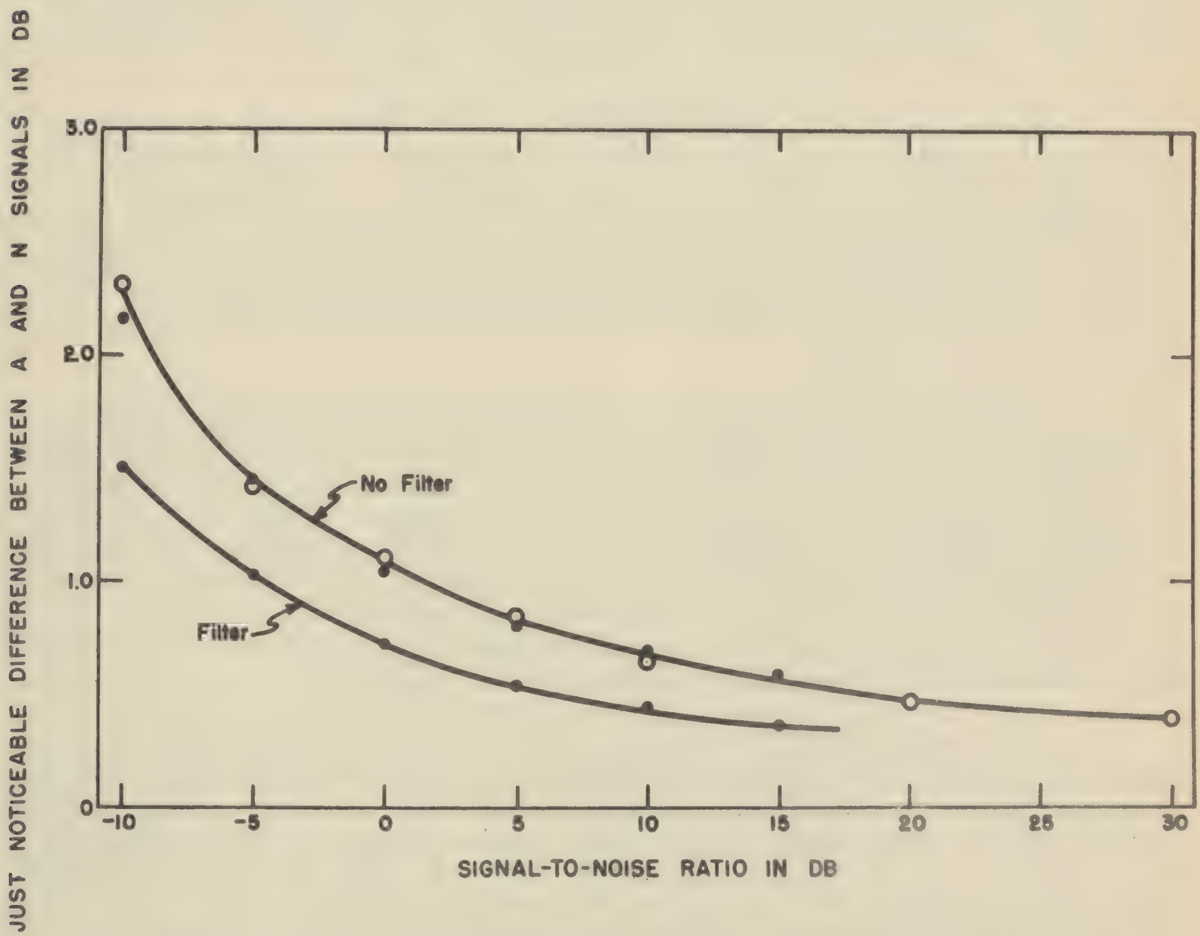



Fig. 14. Mean threshold values for discriminating "A" and "N" code as a function of signal-to-noise ratio. Note the superior performance resulting from the use of a selective filter. (From Flynn, 1945).

At any moment the ear is responding to a relatively small time-band of signals, i.e. the flow of nerve impulses up the eighth nerve is a function of the immediately preceding stimulus. Its sensitivity (adaptation level) may change slowly with time, but its integrative or

"memory" ability is small. Because of this characteristic it sometimes is advantageous to build integrative or "memory" characteristics into signal detection circuits, and thus to assist the ear in detecting repetitive patterns heard against a background of random noise.

Accuracy in Discriminating Different Signal Patterns. Another way to improve signal intelligibility is to choose signal patterns that can be discriminated easily from one another. At one time an E (dot) and T (dash) keying system was employed on radio ranges used in Great Britain. Browne (1943) compared the number of errors made in recognizing the British E-T signals with the errors made with the American A-N system and found the latter to be superior. He also concluded that there is an optimum speed of transmission (approximately 24 letters per minute) above or below which accuracy of recognition suffers. The speed with which an individual can interpret code sounds, rather than speed of sending, is the factor that usually limits transmission rates.

Seashore and Kurtz (1944) analyzed 29,000 errors made by students in copying dot-dash code, and determined the order of difficulty of code characters and the frequency of confusion between different pairs of characters. As was shown to be the case with numbers, they found definite preferences or population stereotypes for copying certain characters. Students also tended to write letters in place of numbers. It is of interest to note that the E-T pair was found to be more frequently confused than was the A-N pair.

Flybar. An interesting attempt has been made to devise auditory signals that can be substituted for visual cues in complex perceptual-motor tasks. The system has been called "Flybar"--flying by auditory reference--because of its application to aviation. It was first demonstrated as feasible in flight by de Florez (1936). Further research was undertaken at the Harvard Psycho-Acoustic Laboratory in order to determine how well continuous control adjustments could be made in response to different signal combinations, and how many simultaneous auditory signals could be responded to successfully (Forbes, 1946).

Various complex auditory signals were tried. Combinations of separate tones proved to be unsatisfactory, since subjects often became engrossed with one signal to the exclusion of the others. One moderately successful complex signal was devised. It combined the following three indications: (1) a "turn" signal that could be made to appear to sweep from right to left, or vice versa, by reason of an intensity shift between the two ears; (2) a "bank" signal that could be made to appear to "tilt" by means of a change in pitch of the carrier tone during each sweep; and (3) an "air speed" signal that took the form of a "beep" at a rate that varied from 2 to 22 per second. This three-in-one signal was reported to be realistic and relatively easy to interpret. Subjects successfully "flew" a Link ground trainer on a straight course with only these auditory cues for guidance.

## Voice Communication Systems

A great many psychological considerations enter into the design of equipment used for the detection, transmission, and reproduction of human speech sounds. In fact, this is the most important area in the design of auditory displays. Stimulus factors that influence the detectability and intelligibility of speech are covered in other chapters of the Handbook of Experimental Psychology, however. For this reason discussion of voice communication systems is omitted from the present chapter. For a further summary of research on a great variety of psychological problems in the design of communication systems the reader is referred to Miller and associates (1946).

## Visual Versus Auditory Displays

Developments such as "flybar", which substitute auditory for visual cues, and new devices such as television and facsimili, which substitute visual displays for speech sounds, raise the question of the relative advantages of visual and auditory displays. This general problem touches the display of all types of information.

Advantages of Each Sense Modality. Each sense modality has certain inherent advantages and disadvantages with respect to the detection and analysis of different kinds of information. Audition is more nearly a continuous sense than vision, because it does not select among the sound pressures that impinge upon it. Vision is basically a selective or intermittent sense, since it is in touch with the world of light waves only when the eyes are open and can then discriminate accurately only a small area near the fixation point. As a consequence, audition is well adapted for the detection of warning stimuli that may arise at any moment from one of a variety of sources, while vision is well suited to the selection of and concentration on particular stimuli to the exclusion of others. Many other differences exist. Craik (1948), for example, pointed out that the ear is better than the eye in distinguishing a constant pattern from a varying background, such as in detecting the beating of a submarine's propellers in the total pressure pattern picked up by a sonar device.

Simultaneous Use of Two Sense Modalities. There are some tasks, such as the search for weak radar signals, in which simultaneous use of both visual and auditory displays may provide mutual reinforcement. The display of different information to different sense modalities, either simultaneously or in alternation, has been suggested by various writers. One of the chief arguments advanced in favor of this idea is that use of auditory cues in complex control tasks should lighten the heavy work load often carried by the eyes. This contention is plausible, but experimental data are lacking with respect to important assumptions

underlying it. In particular it has not been demonstrated in perceptual-motor task that it is easier to respond to a combination of visual and auditory data presented simultaneously, than to respond to the same information presented entirely by means of visual displays. Display systems employing two sense modalities may necessitate rapid fluctuation of attention between the two sense fields. If this is true, and if the human is essentially a "one channel" system, then the use of a "mixed" system may well increase rather than reduce the load of the operator, at least for tasks that profit from close attention. However, once a skill reaches the level at which it becomes essentially automatic, it is possible that bi-modal sensory control may become quite efficient. The hypothesis of a psychological refractory period, discussed in a later section, proposes that central or motor processes, rather than receptor processes, limit the speed of responses in continuous tasks. If this is true it is a further reason to doubt the advantage of bi-modal displays. The judicious combination of visual and auditory displays in various kinds of tasks remains an interesting, if relatively unexplored, possibility.

Visible Speech. Recent developments indicate that it may be feasible to transform electrical patterns of speech into two-dimensional visual intensity patterns (and perhaps patterns of color) which can be "read". A method of depicting speech sounds so that visual recognition and interpretation is possible would be of great value to the deaf, to language teachers, and to those interested in studying the nature of speech and vocal music.

Work on visible speech was begun at the Bell Telephone Laboratories before World War II (see Potter, et al., 1947). One of the principles studied as a means of producing visible speech is illustrated in Figure 15. In this system sound pressure waves are converted to electrical signals and these in turn are separated into frequency bands and projected side by side onto the vertical or frequency dimension of a moving phosphor screen, thereby forming an intensity pattern with a time dimension. Sample patterns of visible speech from different speakers are shown in Figure 16. It is too early to evaluate the possibilities of this development. Its success will depend to a large extent on whether or not a method of display can be developed that will enable the average person to learn easily to recognize speech when it is presented visually.

The corollary of visible speech is the conversion of visual stimuli into an auditory pattern so that the blind can read or find their way about by the use of auditory cues. Some preliminary research is being directed at this problem.

## TACTUAL DISPLAYS

Many of the skilled movements made in machine operation are guided by touch. It is desirable, therefore, to improve tactual displays as well as visual and auditory ones. One of the most obvious possibilities is

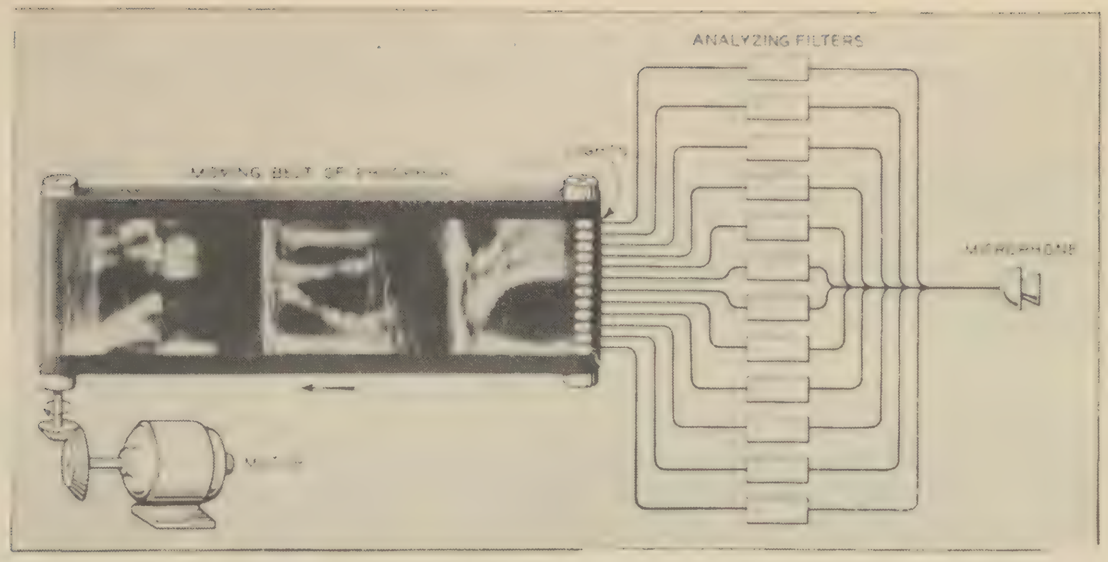



Fig. 15. Schematic illustration of one method for converting speech sounds into "visible speech" (from Potter, et al., 1947).

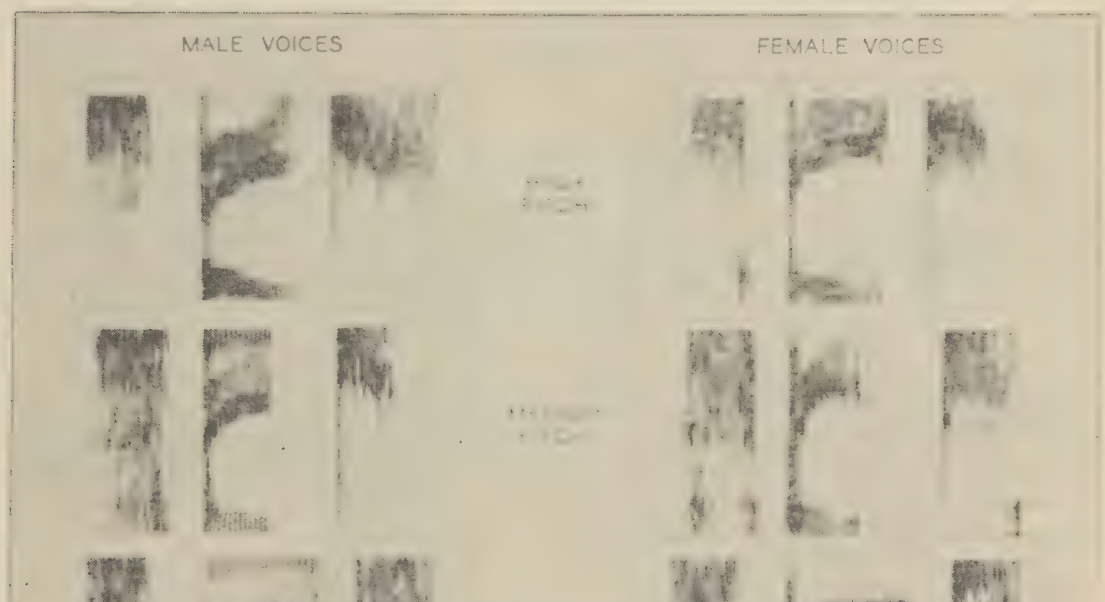



Fig. 16. Samples of "visible speech" from six voices of widely different quality (from Potter, et al., 1947).

to provide machine controls with knobs of distinctive shapes. Studies have been conducted to determine the advantages of shape coding and to discover what shapes provide adequate recognition cues.

Shape Coding of Control Knobs. It has been shown (Weitz, 1947) that use of shape-coded control knobs lessens the amount of interference between conflicting position habits when an operator changes from one arrangement of controls to another. It is an advantage in this situation for the same knobs to be used on corresponding controls in the new arrangement as were used in the old one.

In order for coding to be effective, shapes must be used that can be distinguished easily from one another. An investigation by Jenkins (1947) revealed some of the factors affecting recognition of control knobs. If two objects of the same shape are mounted differently--for example, if one cube is mounted with a flat side up and another cube mounted so that a corner is up--the two are often confused. The orientation of a shape, it appears, by itself is not a distinctive tactual cue.

It was also found that there are families of shapes, the members of which are frequently confused with one another, although they may be distinguished readily from shapes belonging to other families. For example, most shapes with sharp corners and plane surfaces, regardless of the exact number of sides, apparently belong to the same family. Eleven knob shapes that were recognized with practically no errors, even when subjects wore gloves and grasped the knob for only a second or so, are shown in Figure 17.

Size and Color Coding of Controls. Size and color coding have been proposed as a further means for facilitating the identification of controls. Although the provision of multiple cues is theoretically desirable, neither size nor color offer a very practical means of coding controls. Size is a less useful cue than shape because one can recognize a great many more shapes of a standard size than one can identify different sizes of a standard shape. The use of color is limited because it is effective only when the operator looks at the control he is about to use, and then only when levels of illumination are sufficient to permit cone vision. Color, however, has many uses in the coding of both displays and controls as to function. The location of controls, and their mode of actuation, also serve as means of identification. These factors will be considered in the following section.

## DESIGN OF CONTROL SYSTEMS

Man has progressed in the art of control from a state in which he used hand-held tools to fashion the products of civilization, to a stage in which, by adjusting delicate control devices, he directs complex

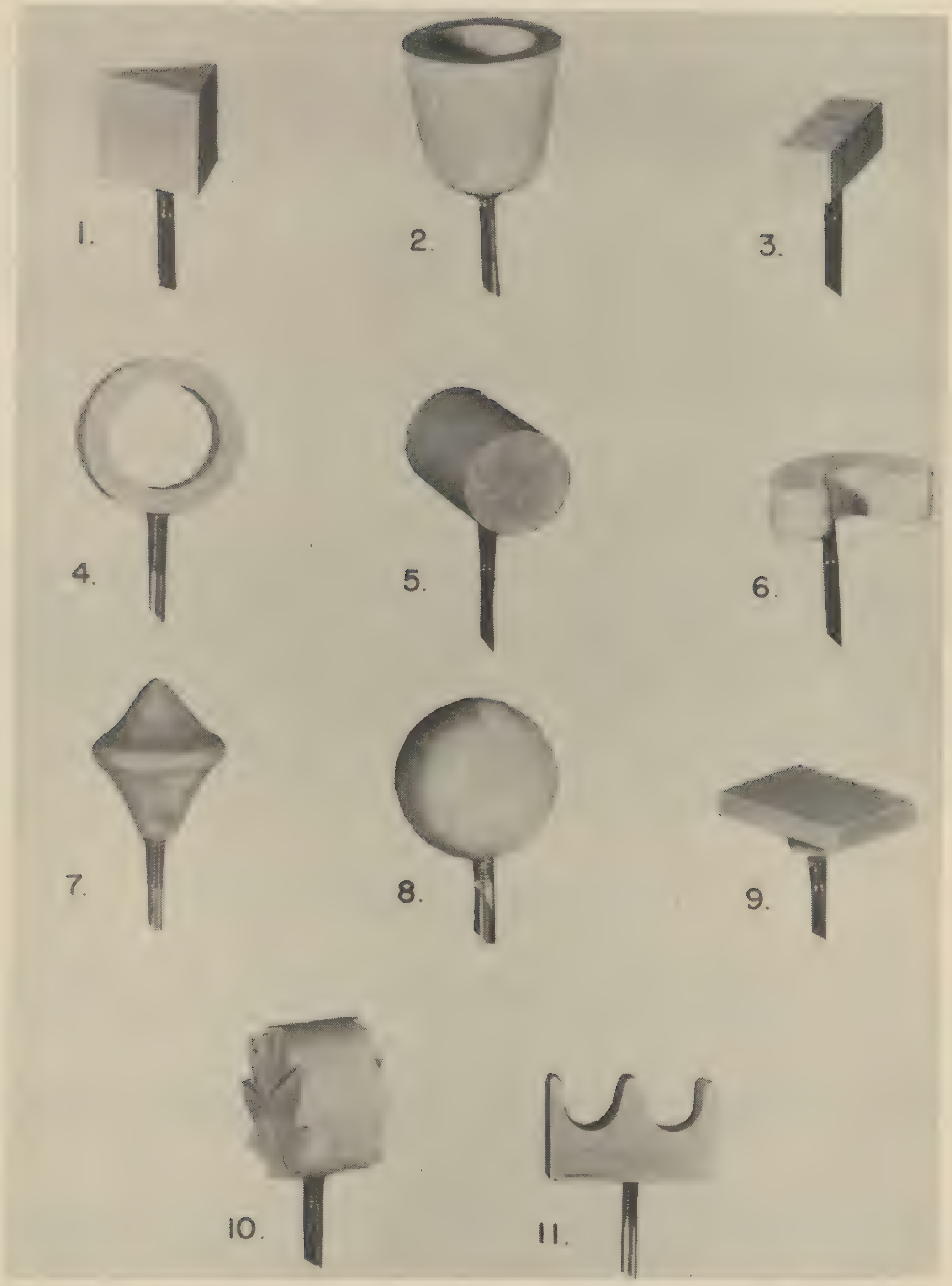



Fig. 17. Eleven knob shapes that are readily identified by touch (from Jenkins, 1947).

machine processes and governs the flow of energy to distant places. With this progress we have seen a shift from power engineering, with its emphasis on economy of energy, to communication engineering, with its emphasis on the accurate reproduction of a signal (Wiener, 1948). Hand-held tools have been replaced to a large extent by machines that utilize external power but require more or less continuous attention from a human operator (steam shovels, lathes, automobiles, home sewing machines). These in turn are giving way to more nearly automatic machines that continue to function for considerable periods of time in the absence of a human operator (automatic pilots, automatic furnaces, automatic home washing machines). Automatons are being developed that operate at an even more advanced level of control--machines, such as high speed computers, that store information, govern their actions by the outcome of intermediate steps, verify their own output, and perform other human-like functions.

Man's role in a technological society is thus becoming more and more one of guiding and directing. Although the tools and simple machines employed by hand laborers and craftsmen can probably be improved somewhat, engineering psychology today should concern itself in large measure with the design of devices that will permit individuals to exercise precise control over large sources of energy.

It is fitting that psychological problems in the design of controls be introduced by a discussion of the transfer and application of force through mechanical and electrical systems. This brief excursion into the field of engineering will give the psychologist a better understanding of the problems met by engineers who must design control systems in which human beings perform critical acts. It will also introduce the reader who is unfamiliar with recent developments in control theory to a point of view that holds considerable promise for the fundamental study of perceptual-motor behavior.

## Dynamic Aspects of Physical Systems[1]

Transmission of Forces through Elastic Bodies. The characteristics of an elastic system that are important in absorbing, dissipating, or transmitting the forces acting on it are its mass, its stiffness or rigidity, and the friction developed during its movement, or the chemical or electrical equivalents of these factors. The mathematical representations of these characteristics are referred to as system constants. The behavior

[1]The assistance of R. C. Gibson, Department of Electrical Engineering, USAF Institute of Technology, in formulating this section is acknowledged.

of an elastic system will depend on these constants and on the forces applied to it. This is true for simple mechanical systems that transmit forces only, and for control systems in which an input signal of low energy governs the output of an amplifier or some other device that provides a source of additional energy.

Lag and Oscillation. Two important problems that arise in designing control systems are lag and oscillation. Lag is evidenced by a time delay between the input and output sides of a transmission or control system. In systems subjected to cyclical inputs delay time often is expressed as the fraction of the cycle by which the output lags behind the input (phase lag). Lag is a universal characteristic of human motor behavior. In the case of the human it consists of reaction time plus movement time.

Oscillation is evidenced by an output that overshoots the correct position one or more times before it settles down. Oscillation, or "hunting", often results when high corrective forces are developed by or act upon members with large effective mass and relatively small energy-dissipating elements. As lag is reduced by the use of large initial forces, application of the exact amount of braking force needed to stop the movement at a precise point becomes more difficult and, therefore, oscillation tends to increase. If after the initial disturbance oscillation builds up in a control system, then the system is unstable. Response curves with different amounts of oscillation are illustrated in Figure 18.

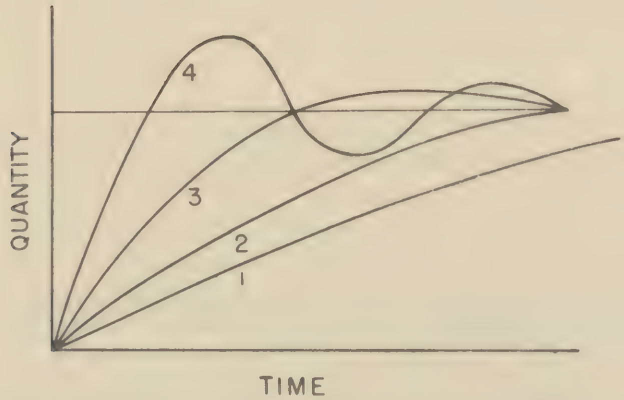
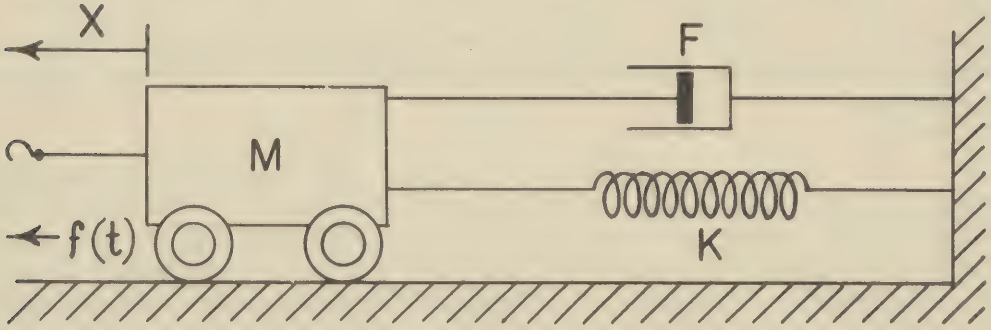


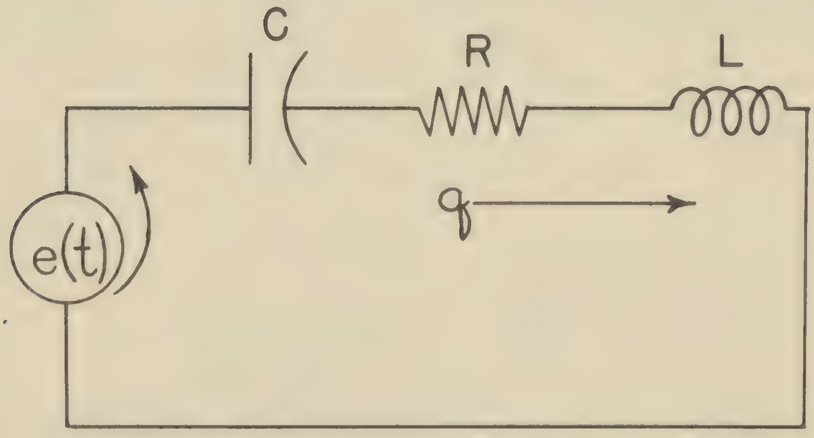

Fig. 18. Response curves illustrating different amounts of oscillation. Curve 1 illustrates overdamping, curve 2 critical damping, and curves 3 and 4 underdamping.

The relation between the input and the output of a control system can be expressed as a function of time by means of a system equation. If such an equation is available, then the amount of lag and oscillation can be determined for any specified input. System equations can be employed to describe the behavior of large, complex systems, or of small units of a system. Often these equations can be determined for a total system even though the characteristics of some of its units are unknown.

System Equations. A diagram of a simple system containing a mass, a spring, and a damper is given in Figure 19-A.




A




B

Fig. 19. Diagram of a simple elastic mechanical system, A, and an analogous electrical circuit, B.

If a time-varying force, f(t), is applied to the mass (M) the internal opposing forces in the system may be equated to the applied force as

$$K\,x + F\,dx/dt + M\,d^2x/dt^2 = f(t) \qquad (3)$$

where x represents the position of the mass with respect to its rest position, $dx/dt$ the velocity of the mass, and $d^2x/dt^2$ the acceleration of the mass at any instant. A special case, often called the transient solution, results if the mass is displaced from its rest position and

released at a time arbitrarily called zero. Then the subsequent behavior of the system can be described by an equation of the form

$$Kx + F\frac{dx}{dt} + M\frac{d^2x}{dt^2} = 0 \tag{4}$$

The mass may overshoot its rest position and proceed to oscillate with a decreasing amplitude but a constant frequency (as a car does after hitting a single bump), or it may return to its former position slowly without oscillation, depending upon the relative values of the system constants K, F, and M.

The dynamic behavior of a simple electrical circuit such as that shown in Figure 19-B can be described by the following equation

$$\frac{1}{C}q + R\frac{dq}{dt} + L\frac{d^2q}{dt^2} = e(t) \tag{5}$$

in which K, F, M, x, and f(t) are respectively replaced by capacitance C, resistance R, inductance L, electric charge q, and electromotive force e(t). The term dq/dt then represents the time rate of change of electric charge and is more familiarly known as current. The transient performance of the mechanical system can be duplicated in the electrical circuit by making e(t) = 0 and placing an initial charge across the condenser at t = 0. This same type of equation can also be used to describe numerous chemical reactions.

In setting up system equations engineers follow well established laws governing the cyclical aspects of natural phenomena. For example, equations (3) and (4) conform to Newton's Law which states that to every force there is an equal and opposite reaction. The opposing forces here appear on the left-hand side of the equations and consist of stretching the spring K, by an amount x, moving the viscous damper F, at a velocity dx/dt, and accelerating the mass M, by $d^2x/dt^2$. Inherent also in the treatment of these systems is the principle that certain components tend to perpetuate a motion, and other components to check or reverse it.

In solving system equations two general types of operations are possible. One is to measure directly each of the constants in the system. This is not always possible. The other approach is to apply known inputs to the system, to record the resulting outputs, and to infer the relative magnitudes of the system constants from mathematical analysis of these input-output data. In practice it is convenient to determine certain ratios between the system constants, such as the undamped natural frequency, $\sqrt{K/M}$, and the damping ratio, $F/2\sqrt{KM}$. Response curve no. 2 in Figure 20, for example, represents a damping ratio of one and is said to be critically damped. Curves 3 and 4 have damping ratios less than one and are said to be underdamped. At present the methods commonly used by engineers in the determination of system equations from analysis

of the relation between input and output depend upon an assumption of linearity. This concept of linearity as it applies to the human is discussed in a later section.

Attempts have been made to describe the behavior of isolated muscle preparations and of intact human limbs by equations similar to equation (1) (see Gilson, et al., 1944; Fenn, 1938). The homeostatic processes and general neural activities of the body are also subject to analysis as rhythmic, dynamic processes (see Hoagland, 1949; McCulloch, 1949).

Receptor processes can also be analyzed in this manner. When sensory stimulation is changed from one level to another the physical, chemical, and electrical processes within the receptor reach a new equilibrium in a manner analogous to that followed by the simple physical and electrical models previously discussed. The eye resembles in many respects a chemical system; the receptor organ of equilibrium in the inner ear resembles a mechanical system. Many of the responses of the latter to stimulation, for example, can be predicted from knowledge of the mass and viscosity of the fluids in the semi-circular canals and of the internal diameter of these canals.

We have examined a few of the dynamic characteristics of simple physical systems, and have seen that sensory, homeostatic, neural, and motor aspects of human behavior can to some extent be described in a manner analogous to that followed for physical systems. Theoretically it should be possible, therefore, to analyze the total complex of human perceptual-motor behavior in this way. The human organism is a most complex example of a dynamic system combining electrical, chemical, and mechanical elements. As Searle and Taylor (1948) point out, it is likely that present equations, complex as they are, are still too simple to handle quantitatively the physical and biological processes involved in perceptual-motor tasks. Nevertheless, the physical systems just described provide a useful model for treating, on a qualitative level, the dynamic aspects of human controller tasks.

Control Systems with Feed-Back. The transmission links and control systems discussed thus far have been "open" or one-way systems. To use a human analogy, these "open" systems resemble a patient with *tabes dorsalis* who can send signals to his arm muscles, but, unless he watches the resulting movement, receives no return signals to tell him what his arm is doing. The most important, most recent, and for psychologists the most interesting control systems, are those with feed-back loops. These are commonly called servo or slave systems. The behavior of a servo is governed, not by the input signal alone, but by the difference between the input and some function of the output. Before considering the overall dynamic characteristics of total controller tasks, however, it will be well to examine some of the more limited aspects of human motor behavior relating to the design of control systems.

Every human motor response involves a distribution of force in time and space. This force is generated in the muscles and is transmitted to tools, levers, switches, steering wheels, and other objects by elastic transmission systems, the limbs. If we include only the limbs the system is an "open" one that can be described adequately by reference to its equivalent mass, damping, and stiffness. When we add associated sensory and neural processes the system becomes one with very complex feed-back loops. It is relatively simple to eliminate exteroceptive sensory feed-back during motor performance, but it is exceedingly difficult to eliminate interoceptive feed-back. For this reason some internal feed-back loops are nearly always active during normal human motor responses.

Temporal Characteristics of Discrete Corrective Movements. If an individual moves his arm quickly from one point to another, he may under-shoot or overshoot the point of aim. If the arm is carrying a heavy load, if damping or braking force is inadequate, or if the tenseness (gain or stiffness) of the muscles is too great, the time plot of the response may reveal a series of underdamped oscillations such as are shown in curves 3 and 4 in Figure 18. Most corrective responses made by skilled human subjects to discrete stimuli, however, resemble curve 2 of Figure 18, which shows no oscillation. Instead, individuals usually make a succession of more or less discontinuous movements. Each movement usually represents a separate effort to reduce the error below the magnitude of a just noticeable difference (j.n.d.) or of a minimal movement. Woodworth (1899) called the first of such a series of corrective movements an "initial impulse" and found that it lasted about 0.2 second. The phase during which discrete secondary corrective movements were made he called "current control". Most subsequent investigators have made a similar classification of the elements in adjustive movements. The time interval between the primary and the secondary adjustments probably depends upon the level and complexity of the sensory feed-back loops by means of which control is exercised. Woodworth reported a value of about 0.5 second for the interval between the initiation of successive adjustments during current control in a one-dimensional task. This figure agrees closely with recent findings on the frequency characteristics of successive corrections during continuous one-dimensional tracking tasks.

Analysis of Movements Executed during Continuous Perceptual-Motor Tasks. Stetson (1905) classified rhythmical movements as slow or fast. In slow movements, groups of opposing muscles contract with uneven tension. In fast movements, both groups of opposing muscles may be under tension ("moving fixation"), or they may contract in alternation or "ballistically". When ballistic movements are made at a maximum rate the limb is literally thrown back and forth, single muscle contractions serving to check one movement and to initiate the next. Stetson and McDill pointed out that slow or controlled movements can be modified at any point in their course, but that this is not true for fast movements, especially ballistic or free movements like beating time with a baton.

They observed that "...such a rapid movement cannot be subject to control after it is once started; movement elements occurring at the rate of 10 per second are the units; at most the movements can be modified not oftener than ten times in a second" (1923, p.23). They concluded further that fast movements are predetermined by the preliminary adjustment or set of the individual.

Peters and Wenborne (1936), studying the time patterns of rapid arm movements executed in moving a stylus along a spiral path, concluded that control was accomplished by means of a series of more or less separate and successive variations in rate, and that these separate "motor impulse effects" were completely determined by processes that preceded each phase of the movement.

In certain situations a sequence of several movements appears to be released as a unit. Dodge (1907) thought that several eye fixations were triggered off as a unit when one was reading, and Woodworth (1899) concluded that the same was true of arm movements in a dotting task. Barnes and others (1940), recording eye movements during the performance of skilled factory work, observed that in "therbligs" requiring visual guidance, the eyes left the scene of action 0.06 to 0.24 second before the action was completed.

Records of visually-controlled aiming and tracking behavior usually have revealed a cyclic pattern with a mean frequency of about 2 responses or half-cycle wave forms per second when tracking was done in one dimension (Bates, 1947; Craik, 1948; Ellson, Hill, and Gray, 1947; Hick, 1948; Tustin, 1947; Vince, 1948).

Ellson, Hill, and Gray (1947) identified two types of tracking records in a one-dimensional following-pursuit task in which the subject used a position control system. "Rate-tracking responses" appeared after the operator had achieved a relatively small position error and were evidenced by the generation of a rate of movement of the control handle that approximately matched that of the target (see Figure 20). "Position-tracking responses" were evidenced by single or successive half-cycle wave forms, which were taken to be indicative of discrete successive control movements.

It would appear from these various findings that skilled movements in continuous tasks are not under continuous visual control, but, like the elements in discrete corrective movements, are triggered off in units. This question will be considered later in relation to hypotheses regarding linearity and a psychological refractory phase.

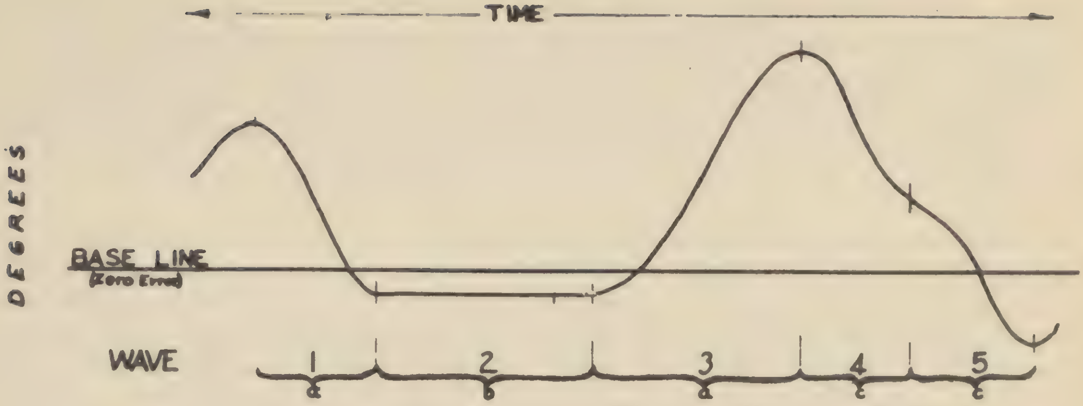



Fig. 20. Section of a tracking record showing three types of responses. A and C are successive position corrections; B is a "rate tracking" response. (From Ellson, Hill, and Gray, 1947)

<ins>Acceleration Patterns during Rapid Control Movements</ins>. Acceleration records sometimes reveal fluctuations in force that are too small to be detected from simple position curves. For this reason psychologists at the Naval Research Laboratory recorded the output from an accelerometer that was mounted on a relatively long (76-inch) control lever (Taylor and Birmingham, 1948). Subjects watched a spot of light on an oscilloscope, and tried to keep it centered by compensatory movement of the control lever. The spot jumped to one side or the other by an amount equal to 1.5, 3, or 6 degrees of visual angle; the appropriate response was a movement of 2-1/4, 4-1/2, or 9 inches, respectively, in the opposite direction.

Smoothed samples of typical position, rate, acceleration, and rate of change of acceleration records for a nine-inch movement to the right are shown in Figure 21. The essential nature of the movement, which was initiated after a reaction-time lag of 0.44 second and lasted for about 0.34 second, was described as follows:

"...For approximately the first 0.07 sec. force in the direction of motion was applied at an increasing rate, then it was applied at a decreasing rate for another 0.07 sec., then braking force was applied at an increasing rate during the next 0.10 sec., and finally the negative force was applied at a decreasing rate for the last 0.19 sec. of the response" (p. 793).

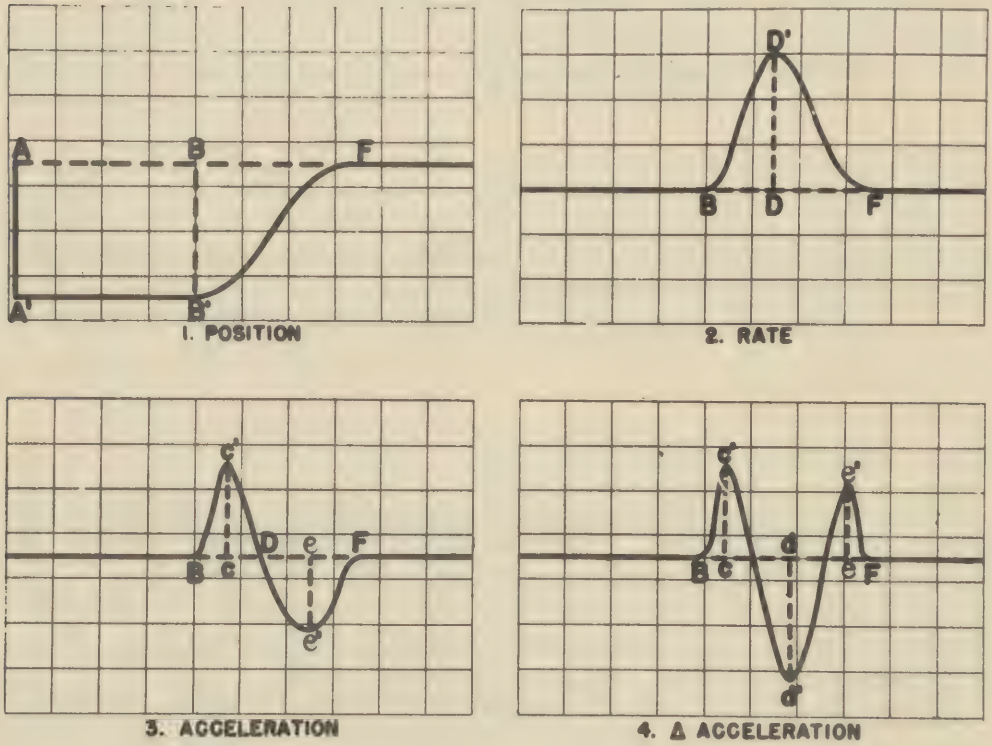



Fig. 21. Smoothed records of the (1) position, (2) rate, (3) acceleration, and (4) rate of change of acceleration of a hand control for rapid corrections made in a tracking task. A-B represents reaction time; B-F represents movement time. (From Taylor and Birmingham, 1948)

There were no ballistic-type movements in which agonists and antagonists showed short bursts of activity with intervening periods of no applied force. Movements appeared instead to be guided by continuously varying forces. Ellson and Hill (1947) likewise found no evidence of ballistic-type movements in muscle-potential records taken during tracking. Evidence from several studies (de Montpellier, 1937; Taylor and Birmingham, 1948) indicates that the time devoted to the positive and negative phases of the acceleration curve varies with the nature of the control task, such as the relative importance of starting a movement quickly or of stopping it accurately.

Reaction Time in Perceptual-Motor Tasks. The delay time before a movement is initiated in response to a stimulus in any particular perceptual-motor task has been found to be independent of the rate, extent, or direction of the specific movement required by the stimulus, and also to be independent of "speed-up" instructions. This is true, of course, only after individuals have been given an opportunity to adjust to the particular situation and task at hand, and holds only for the series of responses made in that situation.

It is extremely difficult to measure directly the reaction time to particular stimuli occurring during continuous tasks and no adequate data for this case are available. Reaction times to discrete stimuli in a series have been reported at values ranging from 0.23 to 0.50 second (Ellson and Hill, 1948; James, et al., 1947, p. 360; Taylor and Birmingham, 1948; Tustin, 1947) depending upon the complexity of the task.

Proprioceptive reaction time is of particular interest here. Craik (1947) reported an experiment in which a lever had to be moved rapidly against a stiff spring so as to correct a misalignment. After individuals had learned the "feel" of the control and were making fairly accurate movements, the spring-tension was altered between responses so that they would tend to over- or undershoot. Under these conditions about 0.15 second elapsed after the beginning of a movement before the individual modified his typical response pattern to meet the changed resistance. Vince (1948a) obtained a figure of 0.16 second for proprioceptive reaction time in a somewhat similar experiment. Hick (1949) however, has questioned these short times and has shown that the inertia and elasticity of the limb is an important factor whenever force must be increased in response to a second stimulus.

In many perceptual-motor tasks, especially those in which information must be secured from several different displays, the latency and perceptual span of vision are important factors. Dodge (1907) postulated the necessity of a "clearing-up" process which he believed precluded a succession of adequate visual fixations under 0.1 second each. Eye fixations in reading seldom are shorter than 0.2 second. More difficult discriminations than those made in reading impose even slower rates on the visual sampling process. Jones and associates (1949) found that aircraft pilots fixated individual instruments for about 0.6 second on the average when making a "blind" landing. Travis (1936) found that the mean latency of eye movements in following a suddenly appearing target was 0.2 second with a standard deviation of 0.02.

In general, then, it appears that responses to proprioceptive stimuli and simple following movements of the eyes take place in an interval approximately that required by simple sensory reactions, but that eye fixations and muscular responses during perceptual-motor tasks are often longer.

Psychological Refractory Phase. The hypothesis of a psychological refractory phase has been developed in reports from Cambridge University, England (Craik, 1947, 1948; Hick, 1948; Vince, 1948) and by some earlier workers (see Telford, 1931). For tasks requiring rapid corrective movements, this hypothesis holds that if two stimuli, $S_1$ and $S_2$, occur in rapid sequence, then the response called for by $S_2$ cannot be initiated until the primary movement in response to $S_1$ has been completed or until an appropriate time interval has elapsed. The exception has been proposed, however, that if $S_1$ and $S_2$ occur nearly together in time they may be responded to as a pair. The fact of cyclic motor responses in continuous tracking tasks has been cited as indirect evidence in support of this hypothesis. The most direct evidence, however, comes from experiments in which two discrete stimuli have been presented in rapid sequence.

Measuring the time required to initiate movements in each of two directions, and using stimuli separated by intervals varying from 0.05 to 1.6 seconds, Vince (1948) concluded that responses to $S_2$ were delayed when $S_2$ followed $S_1$ by less than 0.3 second (approximately the reaction time). Vince's data are given in Table VI. Their interpretation hinges in part on what is taken as a reaction time--whether it is taken as the interval from the appearance of $S_2$ until the movement response to $S_1$ ceases and a new movement response in the opposite direction is initiated, or as the interval from $S_2$ until the movement response to $S_1$ begins to become atypical. The data in Table VI are for reaction times measured in accordance with the former definition.

It appears from the scanty data now at hand that in many response situations there is a real refractoriness when two stimuli occur closer together than a tenth of a second. At these very short intervals acceleration records reveal no changes in the typical force patterns elicited by $S_1$ for periods of at least a tenth of a second, regardless of the time of occurrence of $S_2$ (Warrick, 1948, unpublished data).

It is interesting to speculate that a refractory phase of greater than a tenth of a second may be a necessary condition for the learning of certain tasks. Perceptual-motor learning consists in large part of finding out what kind of functions to insert into the control process, i.e. discovering the gain or tenseness of the muscles that will give the quickest possible response short of instability. On the other hand, discontinuity and refractoriness may be characteristic of situations that favor the modification of behavior. For example, while an individual is learning a new skill he may respond, wait for knowledge of results, then respond again. On the other hand, in situations in which habitual modes of response are utilized, behavior may be continuous or nearly so. This point is also germane to the topic of linearity, to be discussed later.

TABLE VI

REACTION TIME TO TWO STIMULI, $S_1$ AND $S_2$, AS A FUNCTION OF THE INTERVAL BETWEEN STIMULI*

| Interval between Stimuli (Seconds) | Reaction Time to $S_1$ (Seconds) | Reaction Time to $S_2$** (Seconds) |
|---|---|---|
| 0.05 | 0.29 | 0.51 |
| 0.1 | 0.22 | 0.43 |
| 0.2 | 0.28 | 0.41 |
| 0.3 | 0.29 | 0.40 |
| 0.4 to 1.6 | 0.305 | 0.32 |

*From Vince, (1948.)

**Reaction time is here defined as the interval from the onset of $S_2$ until the beginning of a displacement in the dirrection appropriate to $S_2$.

## Optimum Rates and Forces of Movements in Controller Tasks

Some tentative conclusions may be drawn regarding optimum rates of movement and forces to be employed in operating controls. With the present state of knowledge, however, generalizations in this area must be made with caution.

Proprioceptive Feed-Back. The ability of individuals to produce or discriminate variations in force, extent, and duration of movements, and in particular to utilize proprioceptive feed-back, underlies their ability to insert these functions into a control task. Fullerton and Cattell (1892) concluded that the extent of a movement is more accurately judged than its force, and that force in turn is judged more accurately than duration. Woodworth (1901) concluded that discrimination of force and of extent, although related, are separate functions. Hollingworth (1909) studied the discrimination of extent and duration, and concluded that these functions, too, are independent.

Others have suggested that one type of proprioceptive feed-back is primary and others secondary. Morgan (1917) reported that force applied in pulling a weight (against negligible viscous friction) was judged in terms of the duration of the movement. Hick (1945) suggested that when an individual is operating a tracking control against viscous friction, or its equivalent, better performance may result if he concentrates on generating a constant force rather than a constant rate. It has been proposed by Bates (1947) that force can be looked upon as the body's basic output quantity. In accordance with this hypothesis, he reasoned, velocity should be considered the single integral and displacement the second integral of force, and hence, to generate a given velocity or a given displacement should in theory be a more complex operation than to generate a desired force.

The question of the body's basic output quantity has important theoretical and practical implications. It has an important bearing on the design of control systems that will provide optimum proprioceptive feed-back; whether, for example, it is better to require large displacements with small variations in force, large variations in force with small displacements, or large variations in the duration of control acts without reference to their extent or force. Examples of each principle and of combinations of these can be found in many common control devices. Of even more general significance is the question of the relative importance of interoceptive versus exteroceptive feed-back in control tasks and the optimum combination of the two. This question has not been settled. Visual control probably is very important while an individual is learning a new perceptual-motor task. As performance becomes habitual, however, it is likely that internal feed-back or "feel" assumes an increasingly important role.

Aerodynamic engineers have followed the rule-of-thumb that an increment of 2 to 8 pounds of force should produce a maneuver involving an acceleration of one G. The gradient by which back-pressure in a control system increases is especially critical in flying high speed aircraft where a power boost is added to the control and where the response of the aircraft to control movements is slightly delayed (Orlansky, 1949).

Relation between Speed and Accuracy of Control Movements. Woodworth (1899) studied the relation between speed of movements and the accuracy with which they could be executed. When less than 0.5 second per movement was permitted responses made with the eyes closed were about as accurate as those made with the eyes open. Woodworth attributed this to the fact that visual control is of value chiefly during the period of "current control" and concluded that a rate faster than two movements per second does not leave time for the delicate visually-controlled secondary adjustments. He found that slower speeds gave greater accuracy, but that an allowance of about 1.5 seconds per response was sufficient for the completion of all secondary corrections, and that still slower speeds failed to give any

further increase in accuracy. Movements controlled by internal feed-back alone (made with eyes closed) were found to be about equally accurate at all speeds. In this case accuracy was determined chiefly by the initial response rather than by secondary adjustments. When the rate of each movement was constant accuracy diminished as the interval between movements was increased. This was attributed to the fact that the delay between movements led to greater variability of the primary response and hence to a loss in accuracy. For stereotyped, repetitive movements shortening the interval between responses resulted in increased uniformity. Woodworth concluded in this regard that "the path to skill lies in increasing the accuracy of the initial adjustment" (1899, p. 59).

Vince (1948a) repeated and amplified Woodworth's study with similar results. She concluded that the accuracy of movements is affected by speed insofar as, at faster rates, the opportunity for secondary corrective movements is decreased. Errors were small (less than 1 per cent in drawing 1- to 3-inch lines) when more than 0.6 second per response was permitted. When the time between initiation of successive responses was reduced to 0.2 or 0.3 second, however, errors ranged from 7 to 10 per cent of the standard.

When subjects were urged to respond quickly, but were allowed sufficient time to complete all secondary adjustments, Brown and Slater-Hammel (1948) found that the time for the initial movement was decreased, the time for secondary movements in some cases was significantly increased, and the correlation between primary and secondary movement times was negative. In other studies it was found that primary-movement time for left-right movements was less than for inward-outward movements, but that the latter gave shorter secondary-movement times. These results are in agreement with the assumption, based on the analogy of the mechanical system discussed earlier, that there is an optimum gain or stiffness for any response and that efforts to produce higher rates may lead to unfavorable muscular tenseness and loss of fine control, i.e. to oscillation.

Optimum Rates of Movement. The optimum rates of control movements are determined in part by such factors as the maximum rate of muscle contraction, the maximum rate of innervation, and the effect of fatigue. The maximum frequency attainable in repetitive movements of single limbs, such as tapping and wagging the tongue, is approximately 10 per second. Fenn (1938) pointed out that the period of reciprocal movements is similar for different parts of the body, and suggested that frequency is limited by the speed with which excitation and inhibition can be made to alternate in the central nervous system without a loss of precise control over the magnitude of the force. It should also be noted that an appreciable time—about 0.04 second in the human arm—is required for maximum tension to develop in a muscle.

High rates of movement are commonly required in using handwheel controls. Winding movements are a combination of reciprocal movements properly distributed in phase. Their maximum rate is approximately half that of simple back-and-forth movements of similar amplitude. The rate that results in most accurate control has been found to vary with handwheel diameter, inertia, friction, and other design features, and with the type of target course.

In a series of war-time investigations of factors influencing optimum design characteristics of handwheel controls used in tracking, Helson and Howe (1943, 1943a), working at the Foxboro Company, concluded that under any complex of conditions there is an optimum maximum speed. The maximum speeds recommended for different types of handwheels varied from 140 to 200 rpm. Some relations between tracking accuracy and speed of turning are shown in Figure 22 for handwheels of 2.25 inches and 4.5 inches radius. Performance was measured in milliseconds of time error, defined as the time that would be required for the target to move from the point of aim to its actual position. It can be seen that accuracy improved steadily with increasing handwheel speeds up to nearly the human breakdown point. At slow speeds relatively better scores were obtained with a wheel of large diameter, whereas at high speeds the reverse was true. However, the effect of handwheel diameter was relatively small. This finding agrees with the observation that variations in the amplitude of rhythmical movements within wide limits have only a small effect on rate (Bryan, 1892; Stetson, 1905).

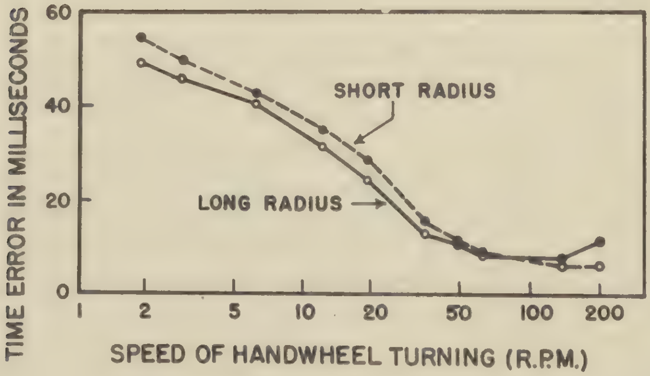



Fig. 22. Accuracy of tracking as a function of speed of handwheel turning. The two curves are for handwheels of 4.5- and 2.25-inch radii, and are based on data from 14 subjects. (From Helson and Howe, 1943)

Optimum Gear Ratios. The ratio between the amplitude of movements of a control and that of its related display has been found to be important for tasks in which a control is adjusted intermittently. Jenkins and Connor (1949) investigated different gear ratios using an apparatus that permitted variation in amplification over a range of 350 to 1 as well as variation both in control-knob diameter and in the tolerance required in the adjustment of a pointer to a new position. Time was measured for the initial movement[1] (called "travel time") and for secondary movements (called "adjusting time").

The duration of the initial movement decreased as the gear ratio increased, until an optimum value was reached. This optimum condition was one where the pointer movement was large relative to that of the control-wheel. Secondary-adjustment time was at a minimum, however, when pointer movement was small relative to that of the control-wheel. The shape of these two functions, as illustrated in Figure 23, was such that a value could usually be chosen that would minimize the overall time required for primary plus secondary adjustments. For most of Jenkins' studies this optimum ratio was approximately one revolution of the control knob for one inch of pointer movement. Variations in knob diameter, in contrast to gear ratio, made little difference in time scores. It should be mentioned that quite different gear ratios may be optimum for other control tasks, such as continuous tasks in which there is no time for secondary adjustive movements or tasks in which there is an appreciable lag.

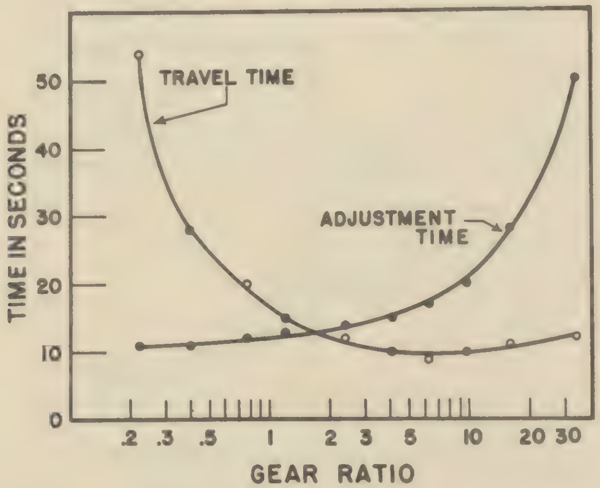



Fig. 23. Travel time and adjustment time for making discrete settings of a pointer by means of a rotary control, as a function of gear ratio. Gear ratio is here defined as the pointer movement, in inches, per revolution of the control wheel. Minimum overall time was obtained for ratios of about 1 or 2. (From Jenkins and Connor, 1949)

[1] The measurement was taken to the time the pointer crossed the correct position; thus underdamped responses gave relatively short times.

Studying the time characteristics of movements, Searle and Taylor (1948) found that, when the ratio of hand movement to pointer movement in a linear tracking task was changed, individuals tended to compensate for the change and to produce a constant rate of pointer movement, i.e. they moved the control at a much higher rate when it was less sensitive.

Friction and Inertia in Controls. Friction that is independent of the speed of control motion (coulomb friction) often has an adverse effect on performance, particularly if it is large in relation to the mass, stiffness, and viscous friction in the system, but it can seldom, if ever, be eliminated entirely. Helson and Howe (1943a) showed that coulomb friction increased the irregularity and average error of handwheel tracking. The effect was least pronounced when high velocities and large inertias were involved. Typical results are given in Figure 24. For situations involving jolting, there is some evidence to indicate that coulomb friction actually has a beneficial effect (Hick, 1945).

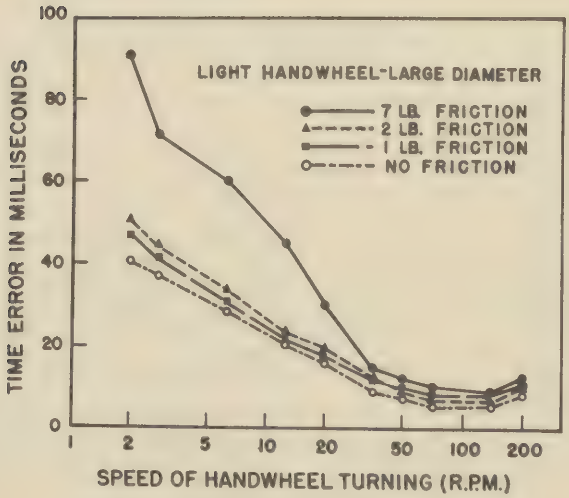



Fig. 24. Effect of friction on accuracy of tracking with a light handwheel of large diameter. Other results indicate that the effect of friction is less marked when a heavy handwheel is used. (From Helson and Howe, 1943a)

Viscous friction, which is proportional to the rate of movement, has been found, in contrast to coulomb friction, to be of definite advantage in many control systems. Inertia, either in the form of a heavy control or a heavy load moved directly by the human operator, has also been found to improve performance in many situations. Some typical results from Helson and Howe's studies of handwheel tracking are given in Table V. Characteristic tracking records with different inertias are shown in Figure 25. Accuracy improved as inertia was increased over a wide range of values. The limit to this favorable increase was reached sooner for small-size handwheels, presumably because excessive force was required to accelerate loads when using a control of small radius.

TABLE V

EFFECTS OF INERTIA AND HANDWHEEL DIAMETER ON TIME-ERROR TRACKING SCORES OF TWELVE OPERATORS*

| Handwheel Speed | Large, Light Handwheel 21 lbs. in$^2$ | Large, Heavy Handwheel 200 lbs. in$^2$ | Small, Light Handwheel 25 lbs. in$^2$ | Small, Heavy Handwheel 197 lbs. in$^2$ |
|---|---|---|---|---|
| 2.0 rpm | 10.7 | 6.6 | 11.1 | 6.8 |
| 2.8 rpm | 9.4 | 5.6 | 8.9 | 4.9 |
| 6.2 rpm | 7.3 | 4.4 | 6.7 | 4.0 |
| 12.0 rpm | 6.4 | 4.0 | 5.4 | 3.4 |
| 20.0 rpm | 8.0 | 4.8 | 5.3 | 3.5 |

*From Helson and Howe (1943a)

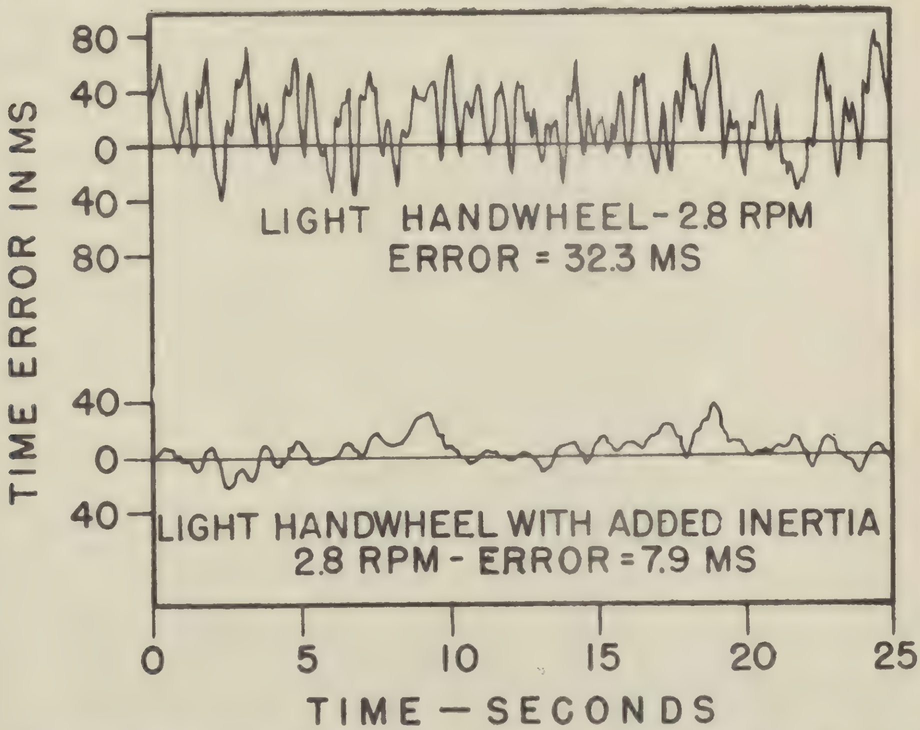



Fig. 25. Two typical tracking-error records, showing the smoothing effect of inertia. (From Helson and Howe, 1943a)

The beneficial results of viscous friction and of inertia are due to several factors. Friction and inertia tend to minimize the effects of small fluctuations in force and to damp out high-frequency oscillations, thus favoring maintenance of a steady output by the operator. This effect becomes especially important under conditions of jolting and vibration. The operation of a control against viscous friction and inertia also provides a basis for discriminating small changes in the rate and acceleration of the load. This corresponds to the feed-back of first- and second-derivative information respectively, and enables the human controller to detect smaller variations in the position of the load than would otherwise be possible.

## Operational Analysis of Human Motor Behavior

We turn now to a consideration of some of the dynamic aspects of complete perceptual-motor processes. A simple servo system with feed-back will serve as a model.

A diagram of a servo system is shown in Figure 26. As before, K and F represent stiffness and damping. J is the moment of inertia of the load. Energy for the servo motor (P) is supplied by the amplifier (A). The error signal $\theta$, which goes to the amplifier, is the difference between the input $\theta_i$ and the output feed-back $\theta_o$ , i.e. $\theta = \theta_i - \theta_o$.

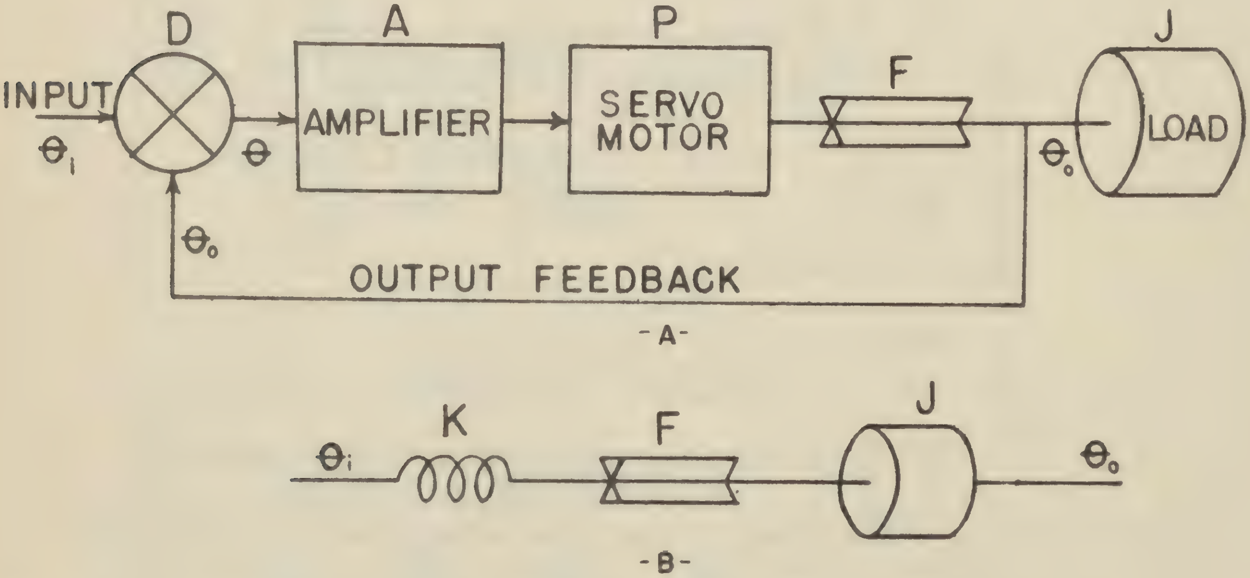



Fig. 26. Diagram of a servo system with a single feed-back loop, A, and an open rotary transmission, B.

In the servo shown in Figure 26-A the torque developed by the motor is equal to $AP\theta$. This torque is opposed by the load J and the damping F on the output so that

$$AP\theta = F\frac{d\theta_o}{dt} + J\frac{d^2\theta_o}{dt^2} \tag{6}$$

or since $\theta = \theta_i - \theta_o$

$$AP\theta_i = AP\theta_o + F\frac{d\theta_o}{dt} + J\frac{d^2\theta_o}{dt^2} \tag{7}$$

An open rotary transmission system is shown for comparison in Figure 26-B. The torque developed in this open system by the spring when $\theta_i$ is turned is equal to $K(\theta_i - \theta_o)$. This torque is opposed by the load and the viscous damping F, so that

$$K(\theta_i - \theta_o) = F\frac{d\theta_o}{dt} + K\frac{d^2\theta_o}{dt^2} \tag{8}$$

Note that equations (7) and (8) are identical if AP = K. The amplifier and motor of the servo are, therefore, mathematically equivalent to a spring, except that the servo utilizes an external power source which is merely governed by the error. Note further that equations (6) and (7) are identical in form to those written for the systems in Figure 19. It should not be construed from this, however, that all control or transmission systems are governed by this simple equation, but only that systems that are physically quite different, such as systems with and without feed-back, may be identical mathematically.

As in the case of the open transmission system considered earlier, a servo system is subject to lag and oscillation. If feedback is continuous, however, the amplifier is kept informed of the lag and oscillation in the output, and it governs the power supply to the motor accordingly.

A function of special interest in servo analysis is the vector quantity relating the output to the input for sinusoidal inputs of different frequencies. This is often called the "frequency characteristic" of the system. Similar problems involving timing, anticipation, and the frequency characteristics of the human being arise in many kinds of human skills, and particularly in control systems in which a human being serves as a link in the system.

Servos may be continuous, as the one just described, or they may be intermittent. A special case of the intermittent system is the definite-correction or sampling servo, which measures the error at regular intervals and after each measurement applies a correction that is proportional to the obtained error value. Servos can be designed to act on different characteristics of the error signal. One possibility is to make the signal to the amplifier include integrals of the error as well as the error itself. This would predispose a system to disregard sudden changes in input and cause it to respond in part to the past history of the error.

Another possibility is to make the input include derivatives of the error. This would predispose the system to respond to rates of change of the error and thereby cause it to anticipate the future course of the error. (For further discussions of servomechanisms see Brown and Campbell, 1948; James, et al., 1947; Lauer, et al., 1947; MacColl, 1945).

If we now substitute the human sense receptors, nervous system, and muscles in place of the servo we have a somewhat analogous system. Input is the desired condition or goal that the individual sets himself to achieve. Feed-back is provided through the eyes, the ears, and other exteroceptive channels, and through the interoceptive channels from muscles, tendons, and joints.

Linearity. The mathematical procedures for setting up and solving equations involving time-varying relations within physical systems are widely known and used, for the limited case in which the relations between variables are linear. The mathematical treatment of non-linear systems, however, is so laborious that it has been a common practice to employ linear approximations as long as the output of a system contained less than 10 per cent non-linear elements. Because of the difficulty of working with non-linear dynamic relations, one of the first practical considerations in applying operational analysis to human perceptual-motor behavior is the question of linearity of the human. This is also a question of general theoretical interest.

For the present purpose it will suffice to define a linear system as one for which the superposition theorem holds. This theorem states that the response to any complex input is equivalent to the sum of the separate responses that would be made to the components of that input. In other words, it is possible to predict the response curve of a linear system to a complex time-varying input by summating the response curves given to separate components of the complex input.

It is well known that the human is basically a non-linear system. At the outset, therefore, the question of whether or not the human is linear resolves into the more specific question of whether there are any circumstances under which human motor responses are linear, or approximately so. Among the most marked non-linearities of human responses are the discontinuities that are associated with learning and change of set. A human being has the ability to adjust many of his "system constants" quickly to suit the task at hand. He can set himself to use different kinds of feed-back; for example, he can try to disregard small error fluctuations, or he can try to respond quickly to the momentary rates and accelerations of the stimulus. He can vary the tenseness of his muscles, the range of forces employed in a movement, and the timing of his responses, until he finds those conditions that give optimum results for a particular task. In addition to the discontinuities that arise during learning, phenomena such as sensory thresholds, sensory adaptation, and fluctuations

in attention and in motivation introduce still other non-linearities. In spite of these obvious exceptions, however, there appear to be some situations in which human motor output is approximately linearly related to input.

It has long been held that some quick corrective movements require approximately the same time regardless of their extent (see Stetson and McDill, 1923). For example, it requires about the same time for a man to write his name, regardless of whether he uses large or small strokes of the pen. It has been stated earlier that the time required for successive movement responses in tracking tasks is relatively constant regardless of the amplitude of the movements. Some data illustrating this relation are shown in Figure 27. These facts are consistent with an hypothesis of linearity, since response curves in executing large movements have a form approximately equivalent to that obtained by superimposing curves made in executing movements of smaller extent.

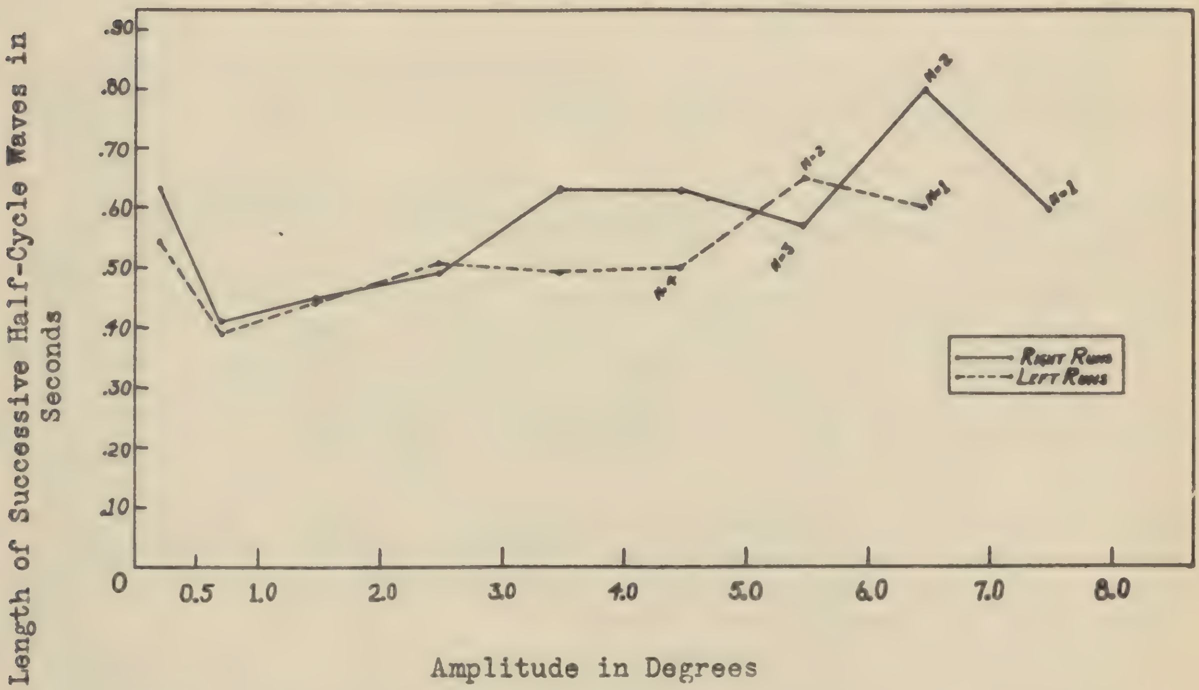



Fig. 27. Relation between duration and amplitude of control movements in a continuous following-pursuit task (from Ellson, Hill and Gray, 1947). The number of cases on which means are based are presented when the number is less than 10.

In testing for linearity it is a common practice to record the output of a system in response to sinusoidal inputs. In a linear physical system, such as an alternating-current amplifier, the output contains the same frequencies, and only those frequencies, that exist in the input. Ellson and Gray (1948) recorded human motor responses in following a simple sinusoidal stimulus motion. They found that after one or two cycles subjects were able to match both the frequency and amplitude of the stimulus up to a breakdown point in the neighborhood of three or four cycles per second. Up to this point, therefore, human responses were essentially linear. The subjects in these experiments also were able generally to keep in phase with the input, although at two or three cycles per second there was a small but definite phase lag. Thus, unlike most purely physical systems, human subjects were able to maintain a uniform amplitude of response for a variety of input frequencies and to compensate for their own reaction time by anticipating the future course of the input with sufficient accuracy to keep in phase with it. In future investigations more complex sinusoidal stimulus motions will probably be employed in order to disguise from subjects the repetitive nature of their task.

Experiments in which discrete responses, either of a following or a compensatory nature, have been recorded also throw light on the question of linearity. Precise recordings have shown that large movements usually require somewhat more time to complete than do small movements when subjects are trying to terminate the movement precisely (Brown and Slater-Hamel, 1949; Taylor and Birmingham, 1948). In the strict sense, therefore, these responses are non-linear. It has also been noted that individuals tend to overcorrect for small distances or forces and undercorrect for large ones. This has been called the range effect. In a statistical sense individuals appear to cause the amplitude of responses to regress toward the mean of the range of responses of which they are members. Woodworth (1899) concluded that constant errors in judging the extent of a movement were at a minimum when several movements of similar extent were made in sequence, and Ellson and Wheeler (1949) showed that the direction of the constant error for different magnitudes of response was determined by the position of a particular response in a series, i.e. by whether it was larger or smaller than other responses in the series, rather than by its absolute size.

In summary, the successive responses made during continuous tracking tasks are approximately linear in the sense that they have an approximately constant duration. Responses to simple sinusoidal target motions are approximately linear as long as the frequency does not exceed two or three cycles per second. In the case of simple repetitive inputs, however, the results are probably accounted for by the subject's ability to recognize and compensate for repetitive stimulus patterns. Discrete corrective responses, in contrast to continuous ones, have been found to be definitely non-linear, movement time increasing somewhat as the extent of the movement increases.

In discussing linearity, Ellson and Gray (1948) proposed the interesting hypothesis that individuals may respond in a more nearly linear manner to complex or unpredictable inputs than to simple or predictable ones. They also observed that responses to different frequencies and amplitudes of input during any one test session were more nearly linear than were responses made during different sessions. This suggests that given individuals may respond linearly for short periods of time.

The general conclusion indicated by the limited data now available is that, while human motor responses on the whole are non-linear and subject to many discontinuities, there apparently are situations in which responses do not deviate sufficiently from linearity to rule out the possibility of using linear approximations in applying operational analysis in the treatment of some controller tasks. Many of the critical tests of the linearity of human controllers have yet to be performed. If it should turn out that human behavior departs too far from linearity to warrant treatment by linear mathematics, it will still be possible to formulate stimulus-response relations in more complicated mathematical terms. Considerable progress has been made recently in the development of the mathematics of non-linear dynamic relations. Also it will be possible to specify the limits within which the human can adjust satisfactorily to different kinds of stimulus inputs and to different controller tasks.

System Equations for the Human Controller. An objective of the study of human control dynamics is the determination of exact mathematical expressions for the stimulus-response relationships in continuous sensorimotor tasks. Such equations would permit predictions from initial sensory input to final motor response; they would be of great practical benefit to engineers; and they would also be of theoretical interest. Psychologists have not yet attempted this quantitative formulation of human behavior in controller tasks, but several engineers have proposed tentative system equations of this nature.

Raggazini (1948) and his associates required subjects to try to keep a spot centered on an oscilloscope by movement of a set of control handles. In this type of compensatory-pursuit task the stimulus contains two components--the predetermined motion imposed on the target by the experimenter and the motion produced by the tracker as he moves the control handles. At intervals, unknown to the tracker, Raggazini stopped the movement of the spot on the oscilloscope, opened the control circuit so that the tracker had no control over the spot, and recorded the movements imparted to the control handle by the tracker during the next few seconds. In this "open loop" situation the stimulus remained fixed but the subject presumably continued for a short time to behave as he would in a continuous "closed loop" control task. Raggazini decided on the basis of data obtained in this way that human tracking responses can be approximated by linear equations.

The equation proposed by Raggazini to describe the human response in this particular tracking task is

$$H = \left[ (ap + b + \frac{c}{p}) \; e^{-p\tau} \right] A \tag{9}$$

where A is the position of the stimulus as a function of time and H is the motion of the operator's limb as a function of time. Equation (9) is written in operational form and is equivalent to the following equation written in a form more familiar to psychologists.

$$H = (a\frac{dA}{dt} + bA + c \int A dt) \text{ delayed by one reaction time, } \tau. \tag{10}$$

Equation (10) is a differential equation similar to equation (3) for the simple mechanical system. In the differential form there is no convenient notation for expressing the time delay introduced by the operator's reaction time, which makes the operational form of equation (9) preferable if an actual solution is desired. The terms a, b, and c are proportionality constants. Their relative values indicate the extent to which subjects respond to target rate, target position, and the integral of target position, respectively. Although his equation contains both derivative and integral terms, Raggazini concluded that derivative control is more difficult for individuals to develop than integral or proportional control and that orders of derivative control higher than the first are probably negligible.

In verbal notation this equation states simply that the position of the operator's control handle at any moment is a function of target rate, target position, and the integral of target motion, all at some instant $\tau$ seconds earlier in time.

It has been proposed by Tustin (1947) that human responses contain basic elements that are linear or nearly so, plus subsidiary elements that take the form of random disturbances. If these subsidiary disturbances are in fact random elements, then a "nearest linear law" may be determined. In order to arrive at a first approximation of this law, Tustin employed a following-pursuit task in which he imposed on the target a complex motion consisting of a fundamental frequency and two higher harmonics. This complex target motion was used in the hope that the subjects would not recognize the repetitive nature of the tracking task. The subjects sat in a rotatable power-driven turret and operated three different types of rate-tracking controls. Simultaneous records of the target motion, the displacement of the operator's control handles, and the tracking error (discrepancy between turret and target) were obtained.

Records of control-handle movements for repeated segments of the same target motion were found to be quite similar. In Figure 28 the target course, handle motion, and error curves are indicated for two successive runs by the same tracker. The similarity of successive records of handle movement is striking when it is remembered that the target error, to which the tracker was presumably responding, contained all the random elements that he himself had inserted, plus discrepancies introduced by the gun-turret's servo system.

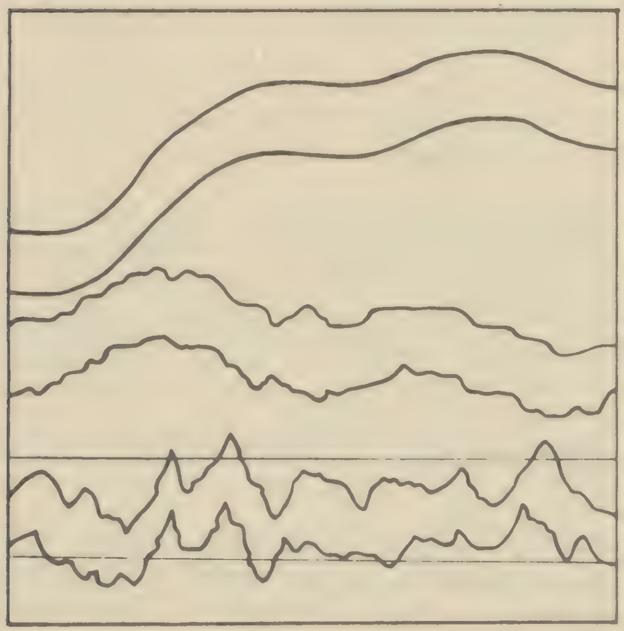



Fig. 28. Records of target displacement, control-handle displacement, and tracking error during two successive test runs by the same subject (after Tustin, 1947).

Records of handle position h(t) and of error e(t) were analyzed to determine the amplitude and phase differences of the subject's responses to the three frequencies contained in the complex target motion. For each frequency the ratio of amplitude of handle motion to amplitude of error signal was determined as well as the associated phase difference between handle motion and error. As a matter of

convenience Tustin here considered the velocity of the tracker's hand motion rather than its position. Based on a trial and error procedure he concluded that handle velocity was related to the stimulus, or error, in the following manner

$$ph = \left[K\ (pT - 1)\varepsilon^{-(0.3p)}\right]e \tag{11}$$

or when expressed in differential notation

$$\frac{dh(t)}{dt} = \left[KT\ \frac{de(t)}{dt} + Ke(t)\right] \text{ delayed by 0.3 second.} \tag{12}$$

Integrating equation (12) we obtain

$$h(t) = \left[KTe(t) + K\int e(t)dt\right] \text{ delayed by 0.3 second} \tag{13}$$

which agrees with equation (10) if we let $b = KT$, $c = K$, $\tau = 0.3$ seconds, $A(t) = e(t)$, and $a = 0$, remembering that Raggazini felt that the derivative term in equation (10) was unimportant.

The fact that two engineers, using different tasks and analyzing their data by different techniques (transient and frequency analysis) independently reached substantially the same conclusions is an encouraging indication that human motor behavior in controller tasks may be mathematically predictable from a knowledge of the stimulus input.

## Effectiveness of Various Human Response Systems

Thus far no special distinction has been made between the effectiveness of different limbs and muscle groups, or of different origins and terminal points of movements. These factors will be discussed in the following section.

Accuracy in Relation to the Muscle Group and Limb Employed in Executing a Movement. The large differences between muscles with respect to strength, method of mechanical attachment to the limbs, and frequency of use would lead one to expect significant differences in the efficiency with which various control tasks can be performed by the fingers, arms, legs, or other body segments. This expectation is confirmed by the finding that the arms give higher scores than the legs in a continuous-pursuit task requiring precise and rapid compensatory movements (Grether, 1947).

When the control task requires that an operator generate small amplitude signals, it is possible to utilize a great variety of motions for producing these signals. Studies of controls for computing gunsights progressed far enough during the war to furnish evidence that a large improvement in overall performance is possible through proper choice of the kinds of movements required for azimuth and elevation

tracking, for ranging, and for triggering (Johnson and Milton, 1947; Bray, 1948). Engineers will be able to take full advantage of this freedom in designing control systems, however, only when the relative superiority of the various limbs, joints, and muscle groups have been fully determined.

The common notion that two hands are better than one is supported by data on position tracking with winding wheels (Helson and Howe, 1943b; Hick and Clarke, 1946) and for position tracking with a sight that was aimed directly at a moving target (Ellson and Craig, 1948). The relative advantage of the independent movement of two separate controls, versus the two-dimensional movement of a single control, when the task is to govern continuously the movement of an object in two dimensions, has not been determined, although two-dimensional controls are considered to be superior and are generally used when this task must be accomplished by one man.

Controls can be designed so that their movement requires the use of different joints. Craik (1944) found that when the amount of movement was expressed in degrees of rotation of the limb about its joint, the variable error decreased with increasing amounts of rotation up to about 2 degrees. Woodworth (1899) called attention to Goldscheider's evidence that sensitivity to angular rotation of the long and short bones is such as to give comparable thresholds for different joints when accuracy is measured in units of absolute arc distance at the extremity of the limb. According to this principle the shoulder should be able to discriminate more j.n.d.'s of angular movement than the other joints of the arm. From this it would be reasonable to set up the hypothesis that greater precision is attainable in using a control properly designed for use by the entire arm than, let us say, in using a control designed for use by the fingers alone. However, other considerations enter into such a practical question.

Accuracy of Movements in Relation to Their Origin, Direction, and Terminal Point. When subjects moved a light-weight control along a track, movements away from the body were terminated more accurately than movements of equal extent toward the body (Brown, *et al.*, 1947). Upward movements tended to be too short in extent, while downward movements tended to be too long. Right-left and left-right movements, however, showed little difference in accuracy.

In following sudden movements of a stimulus, subjects were found to generate the highest rates when moving the right hand from left to right and to generate successively lower rates for forward, left, and backward movements, respectively (Searle and Taylor, 1948).

Corrigan and Brogden (1949) required subjects to move a stylus along a horizontal slot 35 cm wide at a relatively slow speed of 3 cm per second without touching the sides of the slot, and varied the starting point systematically in order to determine accuracy for different directions of movement. Results from 48 subjects are represented graphically in Figure 29. Movements directly away from the mid-line of the body are defined as being at 0 degrees (or 360 degrees). It will be seen from Figure 29 that linear horizontal movements at 135 and at 315 degrees were made with greatest accuracy. If the marked sinusoidal relation between direction and accuracy of motion holds for other controller tasks, this finding has important implications for control design.

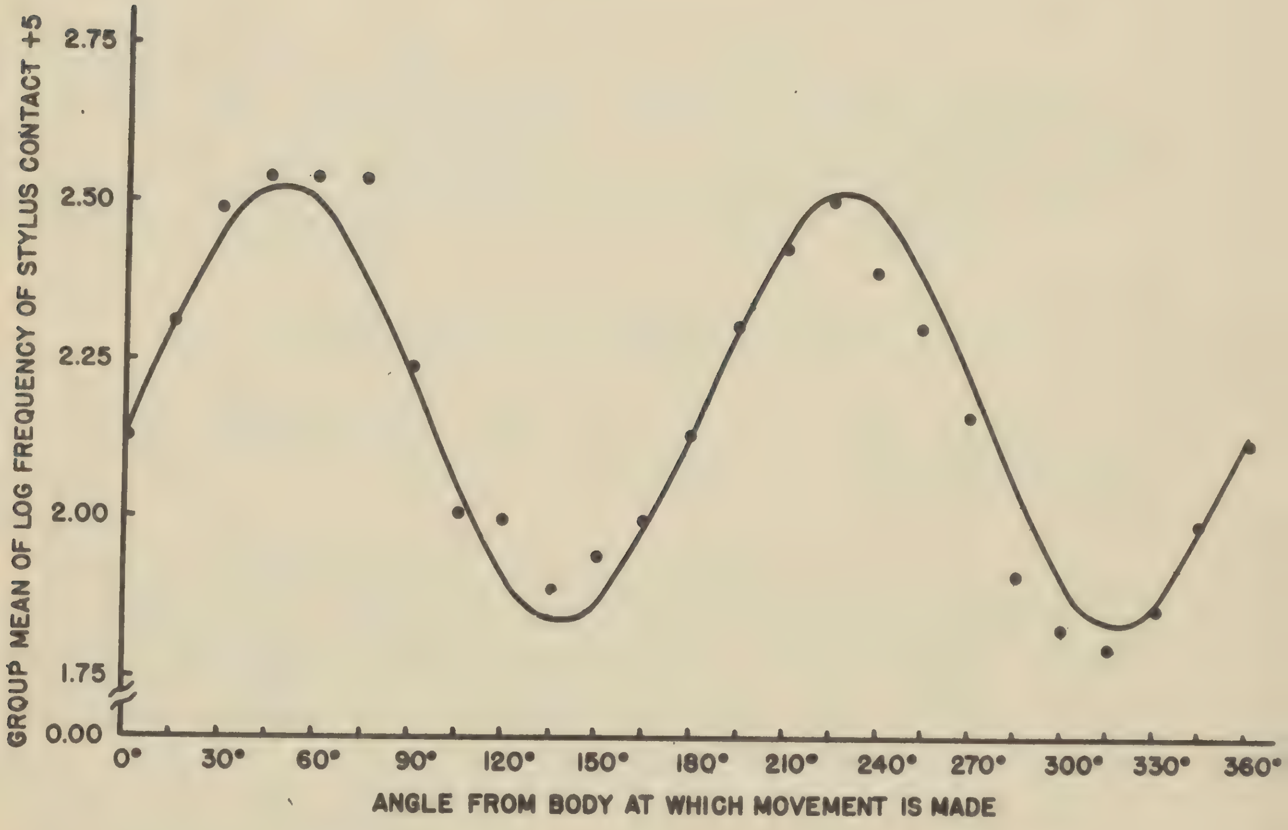



Fig. 29. Precision with which a stylus was moved along a straight horizontal path as a function of the direction of the movement with respect to the body. A smaller score represents greater accuracy. (From Corrigan and Brogden, 1949)

Accuracy in the operation of controls in continuous-pursuit tasks, as a function of the location and orientation of the controls with respect to the body, has been studied by Grether (1947). Fore-and-aft movements of a stick-type control and of a wheel gave a significantly better score than did side-to-side or rotary movements of the same controls. The degree of arm flexion used in operating the controls, however, was found not to be a significant variable as long as it was possible for the operator to move the controls without physical restraint over the entire range of distances necessitated by the task. Thus it appears that operators can be permitted to take up any comfortable position they like in using a hand control.

Vertical, horizontal, and oblique positions of a hand wheel gave equivalent efficiency in another tracking task (Helson and Howe, 1942). Similarly it was found that accuracy in applying force against isometric controls was equivalent for four directions of arm movement (Jenkins, 1947a), and that the position of a crank had relatively little effect on the maximum rate at which it could be rotated (Reed, 1949).

The ability to terminate a free movement with precision in three-dimensional space without visual guidance is important in many machine operations, such as in reaching for a control or an object. Fitts (1947), and Fitts and Crannell(1949) have studied the accuracy of such movements as a function of the location of the reached-for object. Data were collected for 24 different targets that were located perpendicular to a line extending outward from the nearest shoulder and 28-inches away from the shoulder reference point. The reaching motion was initiated with the hands in a position in front of the body and slightly below shoulder height, a common starting point for many reaching movements. Results for a group of 20 college men on the last 3 days of a 12-day training session are given in Table VI. As a general rule localization was more accurate to areas toward the front, below shoulder height, and nearer the origin of the reaching movement, respectively, than to areas toward the rear, above shoulder height, and farther from the origin of the movement. Most areas revealed distinctive constant errors in localization, the most common error being that of reaching too low. In subsequent experiments when reaching movements were initiated with the hands at the sides rather than in front of the body, it was found that targets directly forward were still localized more accurately, but the relative accuracy of location discrimination for various areas was considerably modified. When targets were located only 21 inches from the shoulder points, instead of 28 inches, the absolute accuracy of location discrimination was found to increase, although not by an amount sufficient to indicate that accuracy at different distances can be resolved to a constant angular error at the shoulder. It appears, therefore, that point of origin, reaching distance, and terminal point

all influence the accuracy with which a free movement can be terminated. A conclusion of practical importance is that controls ordinarily should be separated by at least 6 to 8 inches (3 to 4 times the average error of localization) if a high degree of certainty is desired in "reaching blind".

TABLE VI

AVERAGE ACCURACY OF TWENTY PRACTISED SUBJECTS IN REACHING TO DIFFERENT AREAS AROUND THE BODY WITHOUT THE AID OF VISION*
(Accuracy Is Expressed in Inches of Average Error at a Distance of 28-Inches from the Shoulder Point.)

| Location of Targets in an Up-and-Down Direction Relative to Shoulder Point | Location of Targets in a Left-Right Directions: Degrees to Left of Plane Cutting Left Shoulder Point 135° | 90° | 45° | 0° | Degrees to Right of Plane Cutting Right Shoulder Point 0° | 45° | 90° | 135° |
|---|---|---|---|---|---|---|---|---|
| Directly above the Shoulder | | | | 1.9 | 2.0 | | | |
| 45° Upward and Outward | 2.3 | 2.4 | 2.5 | 1.8 | 1.8 | 2.4 | 2.3 | 2.4 |
| Level with the Shoulder | 2.5 | 2.3 | 2.1 | 1.2 | 1.1 | 2.2 | 2.2 | 2.4 |
| 45° Downward and Outward | 2.0 | 2.3 | 2.0 | | | 1.8 | 2.4 | 2.2 |

*From Fitts and Crannell(1949). Data are for the last three days of a 12-day training period.

## Practical Problems in the Design and Arrangement of Controls

Many specific problems are encountered in the design of controls for various devices, and in the arrangement of controls for maximum convenience in sequential operations. No attempt will be made to deal systematically with all these questions. However, brief consideration is given to a few selected topics of practical importance in order to indicate how psychological data can be applied to practical problems.

Design of Perceptual-Motor Tasks for Efficient Learning. The criterion of ease of learning is one of the most important for equipment design. According to existing facts and accepted theory, learning should progress most rapidly and reach the highest levels of efficiency when multiple feed-back of information regarding the results of controller acts is provided, when discriminations are simple and interpretational processes are at a minimum, and when responses can be made directly to the stimulus position or magnitude, rather than to its integrals or derivatives. Learning should be most rapid also when the direction of control movements, mode of operation of controls, and principles of instrument display agree with population stereotypes.

Non-Linear Relations between Controls and Displays. In order to meet varied demands for speed and precision, adjustable or non-linear gear ratios between controls and displays sometimes have been used. For example, low gear ratios have sometimes been provided at one end of a range of control movements in order to assist the controller in executing the small movements, rates, or forces needed in making fine adjustments, and high gear ratios have been provided at the other end of the range in order to facilitate the application of large corrections such as in "slewing" a control. It has been shown (Vince, 1946) that when an individual first encounters a control, he operates it as if he expects to find a linear relation between control motion and display motion. Although individuals can learn to operate non-linear controls, considerable habit interference is experienced when it is necessary to shift rapidly between different controller tasks. Non-linear controls should, therefore, be avoided whenever possible. It will be recalled that a similar conclusion was drawn regarding the use of non-linear scales on visual displays.

Tracking Systems. When an individual moves a control devi e, such as a handwheel, he may cause a similar movement of the output member, or a change in the rate of movement of the output (position or rate control respectively). In a position-control tracking system the operator must continue to move the control as long as the target moves; in a rate-control system, if he can adjust the control to a position that corresponds exactly to the target rate he need do nothing more. Numerous other ways of utilizing human motor output are possible. One system, known as "aided control", has been found to be quite effective for some tasks. In this case a given input produces both a change in output position and a change in output rate. If a watch had a single adjustment that would set the hands ahead when the watch had "lost" a few minutes, and also cause it to run faster thereafter, the adjustment would make use of the "aiding" principle. The ratio of position to rate component in the output is known as the aided-control time constant, or aiding ratio. The optimum time constant of a system will depend on the statistical distribution of rates it is called upon to follow, on

the extent to which the operator can generate derivative control, i.e. respond to the rate of change of the error, and on the operator's reaction time, i.e. how large an error he will allow to accumulate before he makes a corrective response. The more the operator can himself detect and respond to target rate, and the shorter his reaction time, the smaller will be the optimum time constant or aiding ratio (see James, et al., 1947, for a discussion of aiding ratio).

Stability. The problem of stability in control systems is in part that of minimizing lag (such as lag in instruments that provide visual feed-back) and of adjusting the frequency characteristics of the mechanical part of the system to match the capabilities of the human operator over the expected ranges of input frequencies. Displays that combine data from several sources and show only the resultant, such as instruments that mix acceleration, rate, and position information, "aided control" systems that utilize the position, rate, and acceleration characteristics of the controller's motor responses, and controls that provide direct (proprioceptive) feed-back of information about the extent, rate, and accelerations of movements, offer promising means for increasing the inherent stability of man-machine systems. On the one side displays and proprioceptive feed-back can be tailor-made to provide an input that is optimum for the operator's requirements. On the other side man's muscular responses can be integrated, differentiated, or otherwise modified to produce an optimum input for the mechanical part of the system.

Arrangement of Controls. The typewriter presents an example of a control-arrangement problem. Although a standard typewriter keyboard has been in use for many years, the standard arrangement of the keys is poorly adapted to the nature of the typist's task. The work load on the different fingers varies greatly, for example, and is not related to differential finger strength or agility. Dvorak and associates (1936) studied the problem of keyboard design especially with respect to sequential finger movements and found a high proportion of awkward movement combinations. Knowing that 35 digraphs (two-letter combinations) account for half of all typing copy they devised an improved keyboard that permitted a maximum number of successive movements by fingers of the opposite hand or by non-adjacent fingers, and a maximum use of the "home row" keys. This work provides an example of the use of "link values" in solving a specific design problem.

An excellent summary of principles of motion economy that can be applied in designing various controller tasks has been given by Hartson (1939) in a review of research dealing with skilled movements. The results of studies of location discrimination and of the effectiveness of various muscle groups and types of movements are directly applicable to this problem.

## Concluding Remarks

The instances in which experimental psychology can be applied to equipment-design problems are extremely numerous and varied. For this reason it has been necessary to treat a great variety of topics in the present summary. Many of these topics may appear unrelated on first thought, especially if one is interested in some limited response system. Display problems, for example, may seem quite specific when considered apart from the total situation in which the display will be used. Control-design problems may likewise be treated as if the motor aspects of controller tasks were relatively independent of the perceptual aspects. In the last part of the chapter, however, a framework has been developed for tying together numerous aspects of perceptual-motor behavior in continuous tasks as they relate to the design of control systems. This approach treats the human controller as a circular system and offers the basis for a systematic approach to the analysis of the dynamic processes of human receptors and effectors, as well as to the study of the behavior of the total human organism during continuous tasks.

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